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Drying the mystery: a novel electronic sensor to quantify soft-tissue desiccation and natural mummification for forensic taphonomy

Kara S. Adams¹, Devin A. Finaughty^{1,2}, Justin Pead³ & Victoria E. Gibbon¹✉

This study investigates the desiccation process of soft-tissue in South Africa, analyzing its interaction with environmental parameters and its implications for estimating the post-mortem interval. Through the examination of four decomposing porcine bodies across two summer seasons and one winter season, the research quantifies desiccation patterns using custom-designed and constructed printed circuit boards to measure the moisture content of body tissue over time. Generalized additive models were used to determine the environmental forces driving desiccation. Tissue resistivity was tested against the environmental predictor variables to determine the amount of variation they account for, and predicted values of the region-specific tissue resistivity variables were measured for each decomposing body. Results reveal distinct desiccation trajectories between summer and winter, with summer conditions conducive to precocious natural mummification. Environmental factors, particularly temperature and solar radiation, emerge as significant drivers of desiccation. This study represents the first quantitative analysis of deep tissue desiccation internationally, but also the first quantitative assessment of desiccation and natural precocious mummification in the Western Cape, South Africa. The exploration of desiccation as a potential indicator for estimating PMI opens new avenues for research and the integration of innovative methodologies and technologies promises to revolutionize forensic taphonomy practices.

In a taphonomic context, desiccation is the process whereby moisture is removed from tissue¹. Desiccation can be induced artificially through a cultural form of conservation (i.e., mummification) or occur naturally. Often, desiccation of a body requires a hot, arid environment, though the most crucial factor is lack of environmental moisture^{2,3}. Lack of moisture can inhibit the biological activities of bacteria and invertebrate decomposers, excluding them from the decomposition process. It may also render soft-tissue unpalatable for vertebrate scavengers. Therefore, removing moisture slows the decomposition speed, eventually resulting in decomposition stasis⁴.

A specific type of desiccation is known as precocious natural mummification, an alternative form of decomposition defined as the desiccation of whole decomposing bodies occurring in less than one calendar month³. Most literature on the subject relies on case studies, and only a few have been published internationally, including—Arizona², Italy^{5,6}, Bulgaria⁷, Canada⁸ South Africa³. Precocious natural mummification occurs in climatic extremes such as an arid desert², a hot, dry micro-environment such as a sealed house⁵, or as the result of a confounding factor such as extreme trauma to the body⁶. Marella et al.⁶ reported a case where the temperatures and humidity were not representative of the typical conditions associated with the desiccation process, but the decedent had been struck by a train causing extensive lacerations diffusely throughout the body allowing for significant exsanguination. Extrinsic factors such as invertebrate activity have been hypothesized to contribute to the desiccation process. Blow fly larva and bacteria masses can generate their own heat^{9–11} and that process,

¹Division of Clinical Anatomy and Biological Anthropology, Department of Human Biology, University of Cape Town, Cape Town, South Africa. ²Human Variation and Identification Research Unit (HVIRU), Division of Biological Anthropology School of Anatomical Sciences, Faculty of Health Sciences, University of Witwatersrand, Johannesburg, South Africa. ³Department of Electrical Engineering, University of Cape Town, Cape Town, South Africa. ✉email: victoria.gibbon@uct.ac.za

when compounded with high environmental temperatures, increases the rate of insect mortality, reducing their role in decomposition³. Maissonhaute and Forbes⁸ suggest that high levels of insect activity can remove moisture from the body through accelerating soft-tissue liquification, causing the moisture component of the tissue to more readily drain away or evaporate, thus, contributing to the desiccation process.

The phenomenon of precocious natural mummification is of particular interest to the Western Cape province of South Africa given that the process is usually associated with arid conditions, and cases are rarely reported from temperate regions, such as the western portions of the Western Cape where the province's largest city, Cape Town, is located. This region is classified as Csb on the Köppen-Geiger Climate Classification system—temperate, with warm, dry summers and cool wet winters¹². The research conducted by Finaughty and Morris³ represents the first report of precocious natural mummification in circumstances without notable contributory factors in a temperate region globally. During their study, five porcine bodies in the Cape Flats Dune Strandveld environment were fully desiccated in less than 30 days during summer (November–February). The authors also noted this pattern in three local summer season human medico-legal death investigations. It was suggested that such rapid tissue desiccation in the Cape region was due to the unique biogeographic circumstances, inclusive of the summer weather patterns in Cape Town, where transient short intervals of hot, drought-like conditions are observed³. The interaction of these patterns with the carrion entomofauna, notably the dipteran larvae, were proposed to produce the conditions for natural precocious mummification³. However, they highlighted the need for further research to quantify the desiccation process and to confirm its proposed mechanism.

A notable gap in the literature exists to explore and quantify body tissue desiccation. Most published descriptions of tissue desiccation have been qualitative, with only two efforts to quantify the process. Connor et al.¹³ presented a pseudo-quantitative effort to score qualitative descriptions of soft-tissue desiccation and relate the sequential progression of the scores to accumulated degree days (ADD). However, it was Lennartz et al.¹⁴ who first published a quantitative approach wherein they used soil moisture probes to measure moisture content of superficial human soft-tissue. This work offers promise but was limited to the superficial layers of the body, leaving the state of the subcutaneous tissue unassessed. Arrested decay is only achievable when full-tissue thickness desiccation is achieved; therefore, it is imperative to extend Lennartz's¹⁴ approach to deeper layers of soft-tissue. Thus, we sought to develop an original full-thickness soft-tissue moisture sensing modality deployed to monitor longitudinal tissue moisture loss throughout the decomposition processes across multiple seasons and years in forensically relevant locales in Cape Town, South Africa.

Our pilot study is not just about the sensing modality, though. We have established an *integrated method* to study soft-tissue desiccation and provide insight into the mechanisms driving soft-tissue desiccation in the Western Cape region of South Africa. Our method comprises our novel desiccation sensor—integrated within a broader automated technological data collection framework developed by the authors' research group^{15,16}—that provides a roadmap for realizing a previously called-for and much-needed shift in the theoretical conception how the progression of vertebrate decomposition is evaluated, and the underlying processes measured and understood. Specifically, Michaud, Schoenly and Moreau¹⁷ synthesized and presented a strong critical argument against the stage-based paradigm for describing the progression of vertebrate decomposition. This paradigm, based upon qualitative descriptors of the physical appearance of the decomposing body, has come to dominate forensic taphonomy and related disciplines (e.g. forensic entomology, forensic anthropology, carrion ecology)—as seen with Connor et al.¹³ aforementioned effort to understand soft-tissue desiccation. Schoenly, Michaud and Moreau assert that the stage-based, qualitatively founded paradigm represents “typological thinking” and yields “limited use as indicators of decomposition”^{17:p54}. True to form, utilizing the same conceptual framework in forensic taphonomy, forensic entomology, and carrion ecology has hindered these disciplines' ability to develop a comprehensive model of decay which is required for, among other things, the accurate estimation of the post-mortem interval—an oft-sought outcome in forensic death investigations¹⁸. As Michaud, Schoenly and Moreau frankly state, “the widespread adoption and uncritical acceptance of decay stages in carrion research has unfortunately diverted attention from empirical testing of ecological mechanisms and models”^{17:p54}. Ergo, unless we change the way we think about and measure decomposition, we are unlikely to be able to develop a comprehensive, quantitative model of vertebrate decomposition to underpin forensic efforts where decomposing bodies are concerned. Indeed, prominent researchers and practitioners in this space have voiced concern about the efficacy of forensic taphonomy's efforts to develop methods for accurately estimating post-mortem interval based on decomposition (e.g. ¹⁹). Change is needed, and urgently, if forensic taphonomy (and all the disciplines that rely upon knowledge of decomposition and its attendant ecosystems) is to meaningfully assist the medicolegal system.

Our method additionally presents a standardized quantitative approach to evaluate full-thickness soft-tissue desiccation in diverse biogeoclimatic circumstances. The shift towards standardized data collection within the discipline is required to fulfil the Daubert criteria^{20–22}. This shift arises from the fact that many techniques employed in forensic anthropology are subjective, observational, and lack known error rates—an essential requirement for any method to gain practical forensic relevance^{20,21,23}. This extends to forensic taphonomy, wherein standardization of elements of experimental design and reporting has been called for multiple times since 1989 without any serious efforts to address those calls until recently, as outlined in Ref.^{15,16}. Accordingly, our developed method and technology presented in this paper intend to address a range of persistent challenges in forensic anthropology and forensic taphonomy, with wider applications to forensic entomology and carrion ecology.

Results

The weather variables were collected during the two seasonal deployments and the specific values are available in Table 1 along with significant differences between the seasons. The average, maximum, and minimum temperatures were deemed significantly different between the summer and winter. The winter deployment experienced a 24-h mean temperature of 15 °C, which, was 12.7 degrees cooler than that the 24 h mean temperature in the summer. The maximum winter mean temperature was 32.9 °C and comparatively, the mean summer maximum temperature was 39.7 °C, with the cycle MRC S2022 experiencing the hottest temperature at 42.3 °C. None of the cycles reached freezing temperatures, however, MRC W2021 had a 24-h minimum temperature of 4.7 °C. The seasonal difference in rainfall was also significant. The sum of 24-h rainfall was 323.8 mm in winter, which, is 309.6 mm more than in the summer months. The winter 24-h humidity mean was 78.9% which was 7.8% greater than the average 24-h humidity in the summer. The daytime solar radiation in summer was 412.1 W.m⁻², which, is 182.4 W.m⁻² greater than the winter solar radiation. Finally, the winter windspeed was 0.63 km.h⁻¹, which, was 0.87 km.h⁻¹ less than the average summer windspeed.

One of the primary objectives of this study was the development of the printed circuit boards (PCBs) for measuring desiccation. The PCBs obtained measurements of resistance, serving as a proxy for tissue moisture content at various levels within the soft-tissue (see Fig. 1). The detailed technical designs of the PCB desiccation sensor are publicly available at the following Git Repository: JustinPead/tempspike (github.com). The decomposition progression results of the experimental deployments are presented first, followed by the outcomes of the desiccation sensors’ pilot deployments.

Experimental deployments decomposition

Decomposition rate (by proxy of porcine body weight loss in kilograms over time) was determined using a solar-powered automated, remotely accessible taphonomic data collection apparatus^{15,16}. These data are presented in Fig. 2. The summer bodies followed a similar pattern of decomposition that differed noticeably from those in winter. There was a clear and expected difference between the mean weight loss in the summer and winter seasons. In summer, there was a strong inverse relationship between the mass loss and days elapsed post-mortem, while in winter, there was a more linear relationship. In summer, the bodies accelerated quickly through decomposition before plateauing once they reached > 80% mass loss, which occurred around 10 to 15 days into the deployments.

Desiccation of the pig bodies

With the objective to develop a quantitative approach for measuring changes in tissue moisture levels throughout the post-mortem interval, this study focused on the desiccation process, which involves the removal of water from tissue, having the effect of increasing electrical resistivity/decreasing electrical conductivity of the tissue. Custom-designed and constructed PCBs were used to assess desiccation by measuring the moisture content of porcine body tissue during deployments starting in the southern hemisphere summer of 2022. Each PCB featured four zones along its shaft, each zone being equipped with two moisture sensor strips measuring tissue resistivity in ohms (Ω) and a thermometer measuring tissue temperature in degrees Celsius (°C). The shaft of each PCB

Period	Variable	Measure	MRC S2022	UCT S2022	UCT S2023	Summer Mean	UCT W2022
24 hours	Temperature (°C)	Maximum	42.3	38.4	38.4	39.7	32.9
		Mean	23.0	22.5	22.7	22.7	15.0
		Minimum	8.2	12.3	14.7	11.7	4.7
	Rainfall (mm)	Sum	13.2	21.0	6.05	13.4	323.8
	Humidity (%)	Mean	70.9	73.0	69.4	71.1	78.9
	Windspeed (km h ⁻¹)	Mean	2.4	0.37	1.6	1.5	0.63
Daytime	Temperature (°C)	Maximum	42.3	38.4	38.4	37.9	32.9
		Mean	25.9	24.5	25.3	25.2	17.0
		Minimum	8.2	12.3	14.7	11.7	4.7
	Rainfall	Sum	9.1	20.8	4.5	11.5	157.9
	Humidity (%)	Mean	63.0	67.4	62.0	64.1	74.00
	Windspeed (km/h ⁻¹)	Mean	3	0.56	1.9	1.8	0.86
	Solar radiation (W m ⁻²)	Mean	469.3	306.9	460.0	412.1	229.7
Nighttime	Temperature (°C)	Maximum	28.7	30.1	23.9	27.6	24.1
		Mean	18.5	19.3	19.2	19	12.9
		Minimum	8.2	12.5	14.8	11.8	4.7
	Rainfall (mm)	Sum	4.0	0.3	1.5	1.9	165.9
	Humidity (%)	Mean	83.6	81.8	79.6	81.7	84.0
	Windspeed (km h ⁻¹)	Mean	1.5	0.1	1.3	0.9	0.40

Table 1. Average weather variables recorded during the three cycles for 24 h, daytime, and night-time, along with seasonal differences.

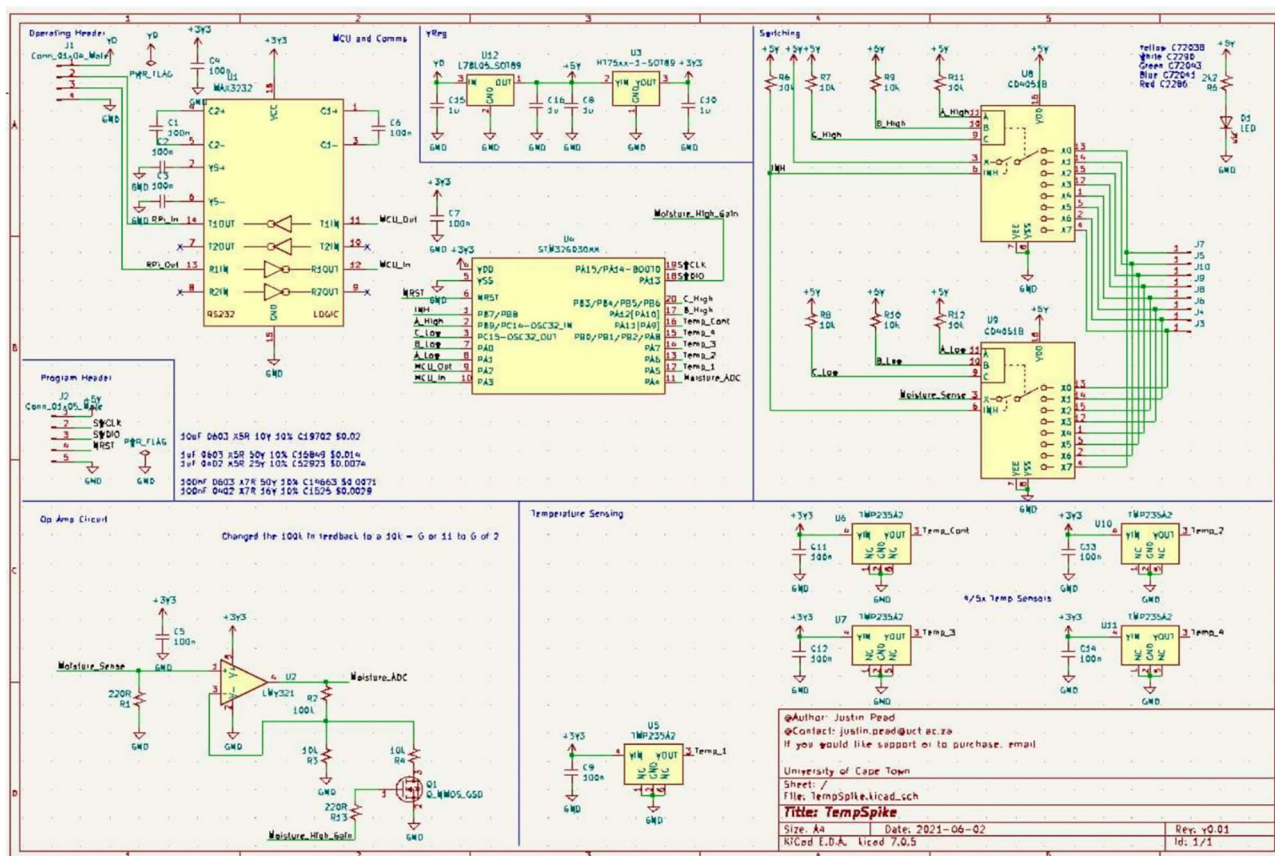


Figure 1. Schematic of the printed circuit boards (PCBs).

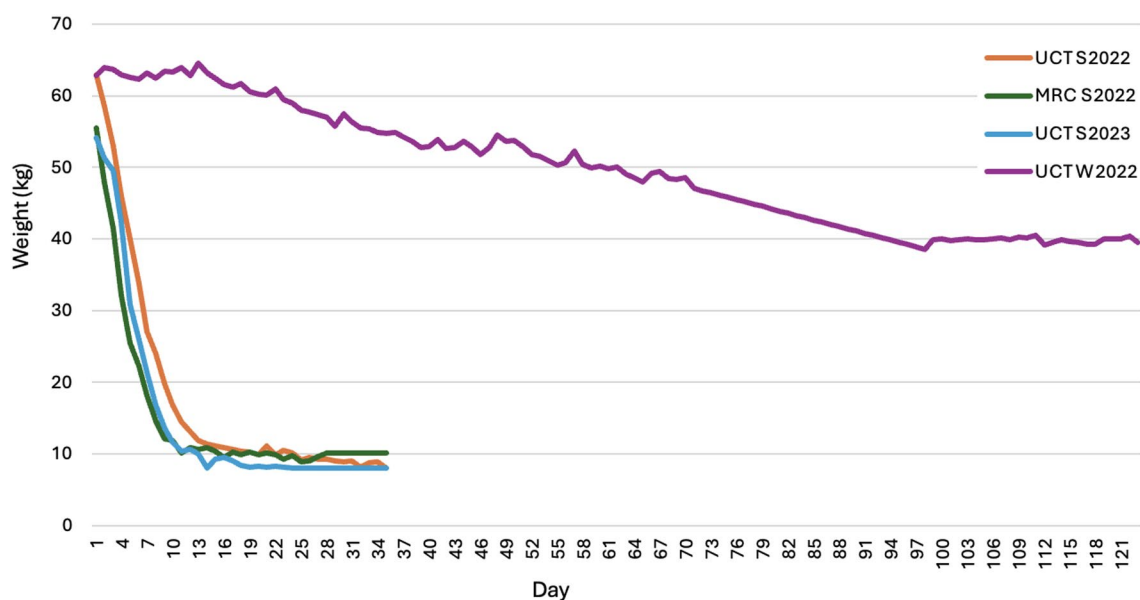


Figure 2. Weight loss (kg) of each porcine body from the following deployments: University of Cape Town Summer 2022 (UCT S2022), Medical Research Council Summer 2022 (MRC S2022), University of Cape Town Summer 2023 (UCT S2023).

was embedded within the soft-tissue up to the body of the PCB. Additionally, a fifth thermometer on the main PCB body served as a control measure for the porcine body surface.

Three PCBs were strategically inserted into each porcine body: one in the head/neck, one in the abdomen, and one in the haunches (Fig. 3). These PCBs were embedded into the soft-tissue up to the body of the PCB, enabling a quantitative assessment of changes in extracellular fluid content through full tissue thickness.

To address the limited sample size, porcine bodies from the University of Cape Town (UCT) and the Medical Research Council (MRC) were jointly observed across seasons. Electrical resistance measurements in ohms (Ω) from sensors in the head/neck, abdomen, and lower body were averaged to provide an overview of the tissue moisture loss (i.e., desiccation) patterns in three summer and one winter deployments. The PCBs employed ratio-level measures of electrical changes in tissue at different levels.

Desiccation rates for each body are depicted as line graphs in Fig. 4. Additionally, individual and collective assessments of tissue resistivity values from the head, neck, abdomen, and lower body were conducted to explore the impact of various weather variables, as presented in Table 1. These data were analyzed to determine if mummification in the Western Cape province follows a predictable pattern, the feasibility of quantifying the desiccation process, and the variables influencing moisture content. Subsequent sections will present desiccation results according to the body region, followed by the development of predictive models for each body region.

Head/neck

The head generalized additive model results are presented in Table 2. The most significant influence in both summer and winter was logADD, which had a negative coefficient indicating that an increase in ADD was correlated with a significant decrease in tissue moisture content. Precipitation was also considered significant in summer, indicating that increased rainfall resulted in increased tissue moisture content or rehydration. The other variables were not significantly related to resistance values. Overall, the weather variables account for 72.6% of the variation in moisture content during summer and 88.6% in winter. Moisture content was plotted against ADD to assess broad patterns of desiccation for both seasons and can be observed in Fig. 5.

Abdomen

The results from the abdominal measurements multi-level mixed effects model are presented in Table 2. The most significant influence in both summer and winter was logADD, which had a negative coefficient indicating that an increase in ADD was correlated with a significant decrease in tissue moisture content or drying of the tissue. Solar radiation had a significant negative correlation in summer and a significant positive correlation in winter. These results illustrate that in summer, an increase in solar radiation was correlated with a decrease in tissue moisture content while the opposite is true for the winter. Humidity was also considered to have a significant negative correlation with resistance, indicating that an increase in ambient humidity resulted in a decline in the tissue moisture content. The other variables were not significantly correlated to moisture content. The weather variables account for 74% of the variation in summer and 37.3% in winter. Moisture content was plotted against ADD to assess broad patterns of desiccation for both seasons and can be observed in Fig. 5.

Lower body

The results from the lower body measurements multi-level mixed effects model are presented in Table 2. Only logADD was considered significant and had a negative coefficient indicating that an increase in ADD was correlated with a substantial decrease in tissue moisture content. The weather variables account for 74.2% of the variation in summer. Moisture content was plotted against ADD to assess broad patterns of desiccation (see Fig. 5).

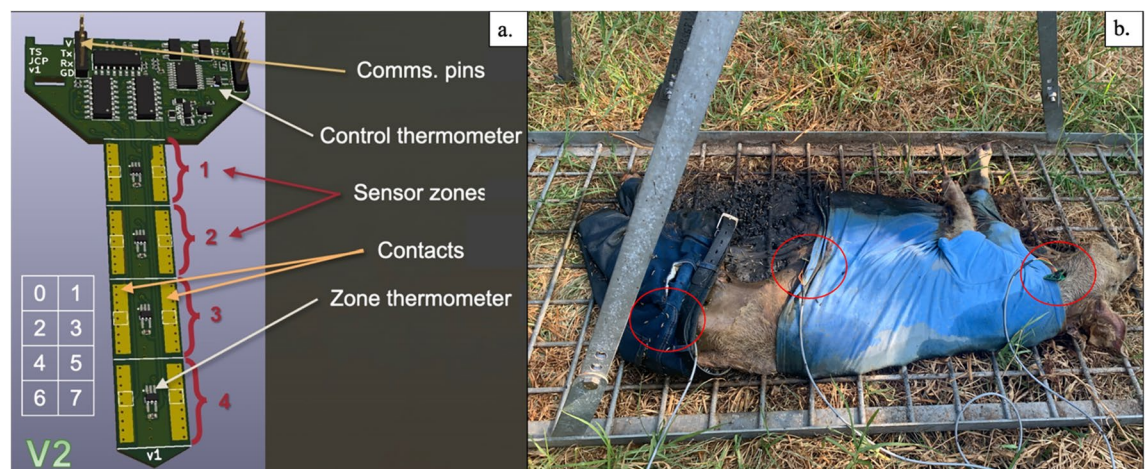


Figure 3. (a) Digitized model of the desiccation sensor and (b) desiccation sensor insertion sites on the porcine bodies (circled in red).

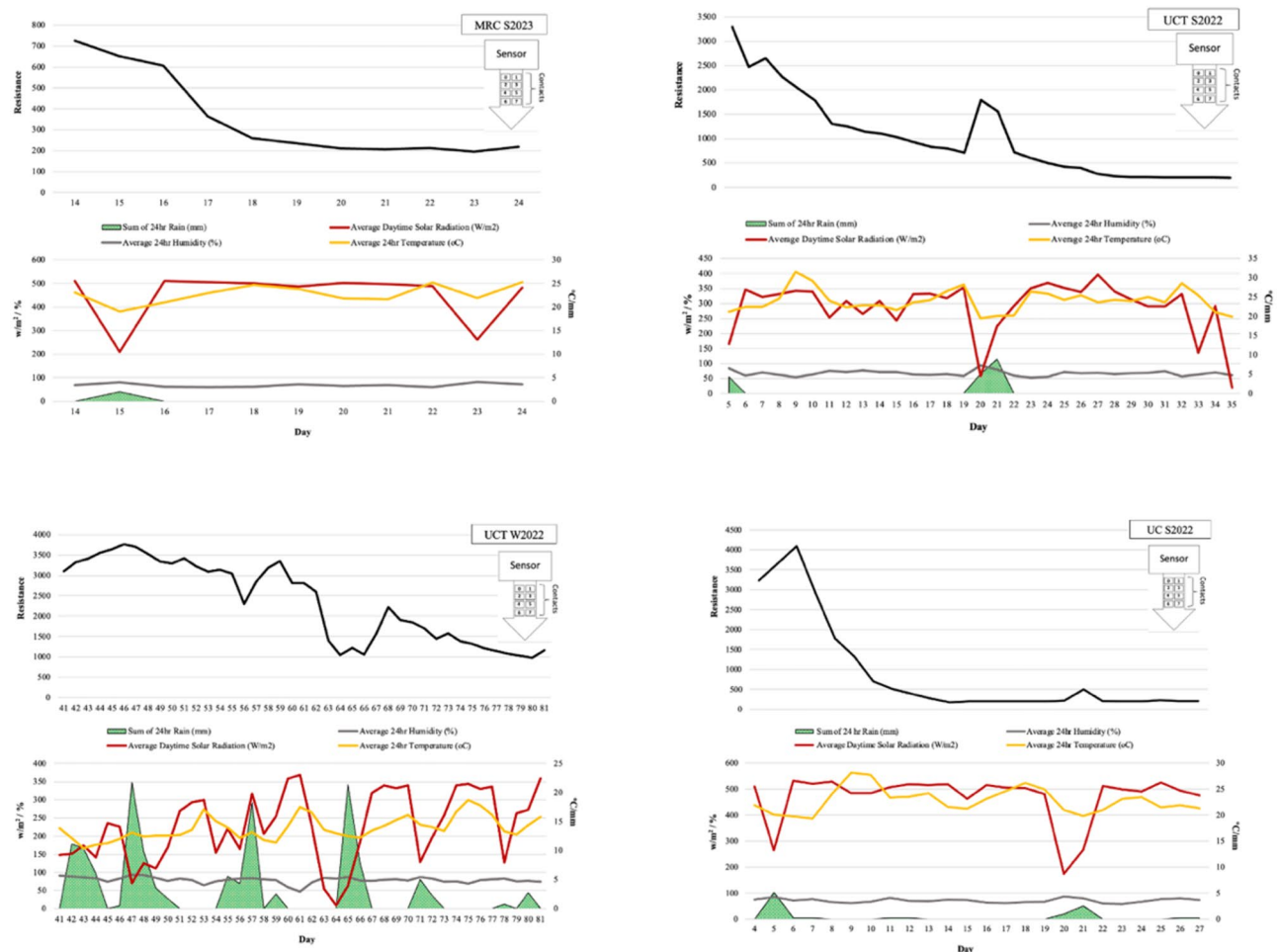


Figure 4. Average of resistance levels (Ω) for University of Cape Town Summer 2022 (UCT S2022), Medical Research Council Summer 2022 (MRC S2022), University of Cape Town Summer 2023 (UCT S2023).

Season	Segment	logADD	Humidity	Precipitation	Solar radiation	R ²
Summer	Head	-1335.85	7.50	196.51	0.50	0.707
	Abdomen	-1999.742	-34.21	-18.47	-7.635	0.717
	Lower body	-1733.95	19.3249	87.96	0.55	0.724
	Full body	-1732.00	0.24	89.36	-1.74	0.782
Winter	Head	-8057.39	-29.70	2.74	2.07	0.873
	Abdomen	-1553.77	17.94	-0.48	2.48	0.304
	Lower body	-	-	-	-	-
	Full body	-4805.58	-5.88	1.13	2.28	0.859

Table 2. Fixed effects coefficients for each body region. Bolded values are considered significant at ≤ 0.05 .

Full body observations

The results from the full body measurements multi-level mixed effects model are presented in Table 2. The most significant influence in both summer and winter were logADD, which had a negative coefficient of -1732.00 (summer) and -4805.58 (winter), indicating that an increase in ADD was correlated with a significant decrease tissue moisture content. Solar radiation also had a significant negative correlation in summer (-1.74) and a significant positive correlation in winter (2.28). These results suggest that increased solar radiation correlated with decreased tissue moisture content in summer, while the opposite was observed for winter. The other variables were not significantly related to resistance values. The weather variables account for 79.6% of the variation in summer and 72.6% in winter. Moisture content was plotted against ADD to assess broad patterns of desiccation for each season and can be observed in Fig. 5.

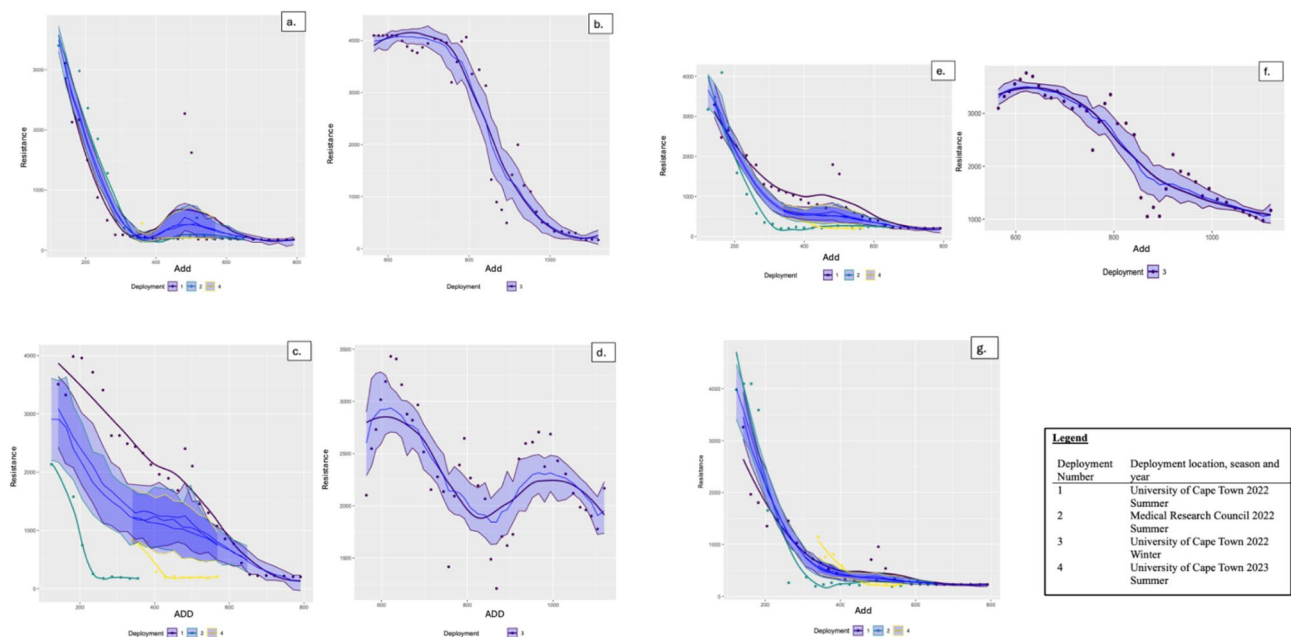


Figure 5. Scatterplot with LOWESS curve data, the y-axis represents moisture content while the x-axis represents accumulated degree days. The blue shaded area represents the statically smoothed (bootstrapped) data. Each graph represents the following (a) head measurements for summer; (b) head measurements for winter; (c) abdomen measurements for summer; (d) abdomen measurements for winter; (e) full body measurements for summer; (f) full body measurements for winter; (g) lower-body measurements for summer.

Predictive models

The following models were created by keeping the fixed effects (temperature; solar radiation; humidity; precipitation) constant and predicting moisture content for various ADD values. These models can estimate moisture content by ADD or the opposite to draw possible conclusions about the PMI based on resistance readings. Using the predictive models (Fig. 6) it is apparent that the head/neck and whole body show the most significant potential as indicators of PMI, as they show the smallest levels of variation.

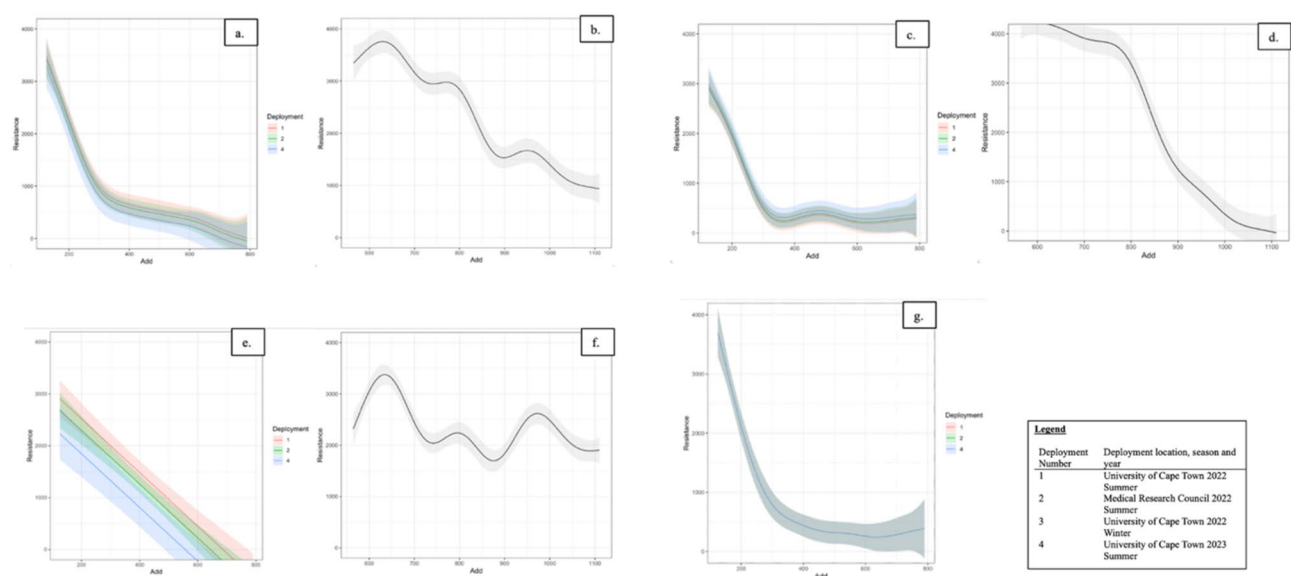


Figure 6. Predictive models where the y-axis represents moisture content while the x-axis represents accumulated degree days. Each graph represents (a) head (summer); (b) head (winter); (c) abdomen (summer); (d) abdomen (winter); (e) full body (summer); (f) full (winter); (g) lower- (summer).

Discussion

The primary objective of this study was to quantify the desiccation process of soft-tissue during decomposition in the Western Cape and explore its interaction with abiotic environmental parameters such as temperature, humidity, precipitation, and solar radiation. Additionally, the study aimed to investigate whether the extent of desiccation could be correlated with the post-mortem interval (PMI).

Connor et al.¹³ proposed a qualitative method using a total body desiccation score (TBDS), correlating well with ADD in advanced decomposition stages. Building on this, a quantitative method using bioelectrical impedance analysis was developed²⁴. Other studies explored surface-level moisture content for correlating with PMI²⁵. This current study extends these approaches, employing custom-designed internal PCBs embedded with conductive plates and thermometers to measure resistance levels (ohms) of full-thickness body tissue at multiple depths in major body regions (head/neck, abdomen, and limbs). Resistivity served as a proxy for tissue moisture content. The study involved four decomposing porcine bodies across three summer seasons and one winter season, exploring desiccation patterns, the 'point of mummification', and the impact of specific environmental factors on soft-tissue desiccation in Cape Town.

Notably, all three summer bodies underwent complete desiccation in less than 30 days, while the winter body entered a state of stasis in advanced decomposition. No adipocere formation occurred during the deployments. Precocious natural mummification, defined as the desiccation of whole bodies occurring in less than one calendar month, has been previously documented in the region^{3,26}. Mummification, characterized by preserved soft-tissue that has undergone desiccation, is typically associated with arid regions with moving air^{5,27}. However, the Western Cape features a temperate Mediterranean climate, marked by cool, wet winters and hot, dry summers.

While decomposition is conventionally viewed as a linear, sequential process, prolonged periods of stasis linked to desiccation are often overlooked or considered outliers¹³. Challenges arise in estimating the PMI using total body score (TBS) in advanced decomposition stages when micro-environments facilitate desiccation¹³. Previous studies in Texas and Colorado demonstrated inaccuracies in TBS predictive models for TBS values exceeding 22^{28–30}. Given the global prevalence of desiccation, there is a need for more tailored methods to estimate PMI for desiccated remains¹³.

In summer, the porcine body regions followed similar patterns of desiccation: an exponential decline in resistance until reaching a plateau where no more moisture was lost. The resistivity of all body regions immediately post-bloat was recorded to be around 3000–3500 ohms, and this value dropped to about 200 ohms (5% of the original value) for all regions. Overall, the pattern of desiccation resembles an exponential decline over time until the rate of desiccation plateaus around ADD 400.

Conversely in winter, the porcine body regions did not follow a similar pattern of desiccation, and the models were non-linear. Resistivity for the areas immediately post-bloat was recorded to be around 3000–3500 ohms, as it was in the summer. However, the head and neck region declined slightly more exponentially and reached a value of about 200 ohms (5% of the original value) at ADD 1076, while the abdomen was non-linear and only reached values of around 2000 ohms (50% of the actual value) at the cessation of deployment. The lower body sensor for the winter body did not produce viable data and was not included in the interpretation.

As outlined by Lennartz²⁵ and Lennartz et al.¹⁴, the mummification point was determined as the stage where tissue ceased to lose moisture or undergo further decomposition. Their findings indicated that a moisture content approaching 10% signified desiccation to the point of mummification, and once this level was reached, subsequent changes were minimal. In our current investigation, the mummification point was identified at approximately 5% of tissue conductivity immediately post-bloat during the summer. Fluctuations exceeding 5% were attributed to rainfall, leading to brief rehydration. Notably, the winter body did not desiccate.

These quantitative data corroborate the results reported by du Toit³¹ from another region of South Africa, who qualitatively explored body tissue rehydration and observed an increased decomposition rate following rehydration. The impact of rehydration varied noticeably with season. In the hot, dry summer seasons characterized by infrequent rainfall, there was a brief surge in conductivity followed by a sharp decline once desiccation resumed. This is supported by the body weight loss data, which shows slight increases in weight during/following a rainfall event, followed by decline in weight loss.

Similarly, the cool, wet winter season experienced frequent heavy rainfall, resulting in an elevated conductivity that was subsequently followed by a rapid decline. However, the decrease in conductivity was slower during winter, indicating that the tissue likely retained more moisture, possibly due to the clothing worn trapping moisture from frequent rainfall. The influence of clothing, acting as a moisture trap, could not be quantified in this phase of the study. Future research endeavors should aim to quantify the desiccation process for both clothed and unclothed remains.

Based on the testing of generalized additive models, the R^2 values indicate that variations in fixed environmental effects explained between 70 and 80% of resistivity variation in summer. In contrast, these effects accounted for between 37 and 88% of variation in winter, depending on the body region. This underscores a component of the criteria proposed by Finaughty and Morris³, who asserted that the distinctive summer weather in Cape Town plays a pivotal role in the observed precocious mummification. They outlined proposed criteria for mummification-inducing weather, including a 24-h maximum temperature $> 30^\circ\text{C}$, mean solar radiation value $> 600\text{ W m}^{-2}$, mean daytime humidity value $< 50\%$, and windy conditions [daytime windspeed/gust measures of $32.19\text{--}48.28\text{ km h}^{-1}$]. Contrary to Finaughty and Morris³ suggestions, precipitation, humidity, and solar radiation were not considered significant factors in desiccation based on this study's results.

Additionally, windspeed never reached the values suggested for inducing desiccation, and since the shade cloth surrounding the decomposing UCT bodies sheltered them from the wind, it was excluded in generalized additive modeling. The highest recorded windspeed was 25 km h^{-1} during the UCT W2022 deployment, but this was an anomaly. The average summer windspeed was 1.83 km h^{-1} and the average winter wind speed was

3.29 km h⁻¹. Solar radiation emerged as the second most significant factor, although daytime averages never reached > 600 W m⁻², as recommended for driving mummification. The highest recorded daytime solar radiation value was 536 W m⁻² during the MRC S2022 deployment.

Connor et al.¹³ noted that high ultraviolet exposure leads to desiccation in both superficial and deep tissues, preserving viscera, cartilage, and muscle structures. Although the current study recorded solar radiation and not ultraviolet exposure, similar findings were observed. The results align with those documented by Lennartz²⁵ and Lennartz et al.¹⁴ highlighting that temperature significantly influences tissue moisture content. Unlike Lennartz et al.^{14,25} humidity and precipitation were expected to have an additive effect on tissue moisture content, which was not supported by the findings. However, while Lennartz²⁵ and Lennartz et al.¹⁴ found solar radiation insignificantly affected desiccation, it emerged as the second most crucial factor in the current study, likely due to its correlation with temperature.

Finaughty and Morris³, asserted that the distinctive summer weather in Cape Town is pivotal for precocious mummification. Another study has hypothesized instead that high levels of insect activity can draw moisture from bodies producing desiccation⁸. However, as documenting invertebrate activity was outside the scope of this study, it is not possible to comment if either of the above situations occurred. Summer weather conditions, characterized by high temperatures, solar radiation, and minimal precipitation, create an environment conducive to desiccation. The study concludes that mummification-inducing conditions in summer include increasing accumulated degree days (driven by high ambient temperatures) and high solar radiation, with secondary influences from high humidity and low precipitation. In contrast, the winter weather in Cape Town does not foster desiccation or mummification, which is consistent with prevailing weather conditions at that time of the year (low temperature, high humidity, and extensive rainfall).

Although this study produced promising results, certain considerations require attention. Decomposing porcine bodies from UCT and MRC were jointly observed across seasons due to a limited sample size. To enhance statistical robustness and explore potential distinctions in the desiccation process between these two locations, future investigations should incorporate additional seasonal porcine body taphonomic deployments at each site, with appropriate location- and seasonal replicates. Examining the impact of scavenging by both vertebrates and invertebrates (notably carrion entomofauna) on the desiccation process is the next logical step for this research towards understanding precocious natural mummification, given that a method has now been established for quantifying full-thickness soft-tissue desiccation.

Limitations

Throughout the deployment, several limitations were observed. Tissue around the PCBs would lose contact with the sensors as it lost moisture, particularly evident during the summer season when decomposing porcine bodies underwent rapid desiccation, and in body regions with thinner tissue such as the head/neck, which decomposed faster. As a result, occasional gaps in data occurred due to sensor detachment from the tissue. Future studies should explore alternative sensor deployment methods, such as medical skin glue, to minimize tissue disruption and data loss. Furthermore, inherent to novel technological applications, instances of missing data due to technological malfunctioning were encountered.

Materials and methods

This study was carried out at two forensically significant locations in Cape Town. Cape Flats Dune Strandveld (CFDS) and Cape Flats Sand Fynbos (CFSF) vegetation represent the vegetation subtype(s) where a large portion of Cape Town's forensic cases come from Ref¹⁸. However, urbanization has destroyed most of the CFSF vegetation; therefore, only the CFDS vegetation is represented in this study. The first site was in a peri-urban CFDS habitat, and the second was in a suburban habitat (Fig. 7).

The first site was the South African Medical Research Council's research facility (MRC) in Delft, Cape Town, South Africa (Fig. 7). Delft is on the Cape Flats, a low-lying, flat area on the southeastern side of the City of Cape Town Metropole. The Cape Flats extend from the Boland Mountains in the east to the Table Mountain range in the west. Delft is a forensically significant region with a dense population of more than 13,000 inhabitants per square kilometer³². Delft reported 277 murders in 2022/2023 alone—more than the whole of London in the same period (London being a city several times the size of Cape Town both in area and population)³³. The site is an outdoor peri-urban environment (UTM 17 T 283009.88 m E 6236344.50 m S), 3.64 acres in size and is located on the west side of the MRC facility (Fig. 7). The entire facility is enclosed by a fence, easily accessed by animals, but deters access by people. The urban settlements of Delft have encroached up to the fence of the MRC, but the site remains adjacent to the Driftsands Nature Reserve, which has one of the largest remnants of CFDS vegetation. As previously mentioned, a large portion of forensic cases come from this vegetation type.

The second site was private land owned and operated by the University of Cape Town (UCT) in Rosebank, Cape Town, South Africa (Fig. 7). Rosebank has a population density of more than 4500 inhabitants per square kilometer³², and it is a relatively low crime area compared to Delft, with only one murder reported for 2022/2023³³. However, it is forensically significant as previous research has found that body disposal in open fields and residential areas in Cape Town is quite common^{18,34–36}. The site was an outdoor suburban environment (UTM 17T 265982.37 m E 6240100.73 m S), 0.09 acres in size, immediately surrounded by recreational sports fields (Fig. 7). The site is enclosed by a fence that excludes almost all terrestrial animal species from accessing the land but permit avians. Rosebank is a suburban area with many residential homes and is located on the eastern slope of Table Mountain, on the other side of the motorway from Table Mountain National Park. The CFSF vegetation was the most representative vegetation for this location. However, urban development has destroyed almost all CFSF vegetation in the area. As a result, this location is representative of typical low-to-medium density suburban environments that make up much of the City of Cape Town.

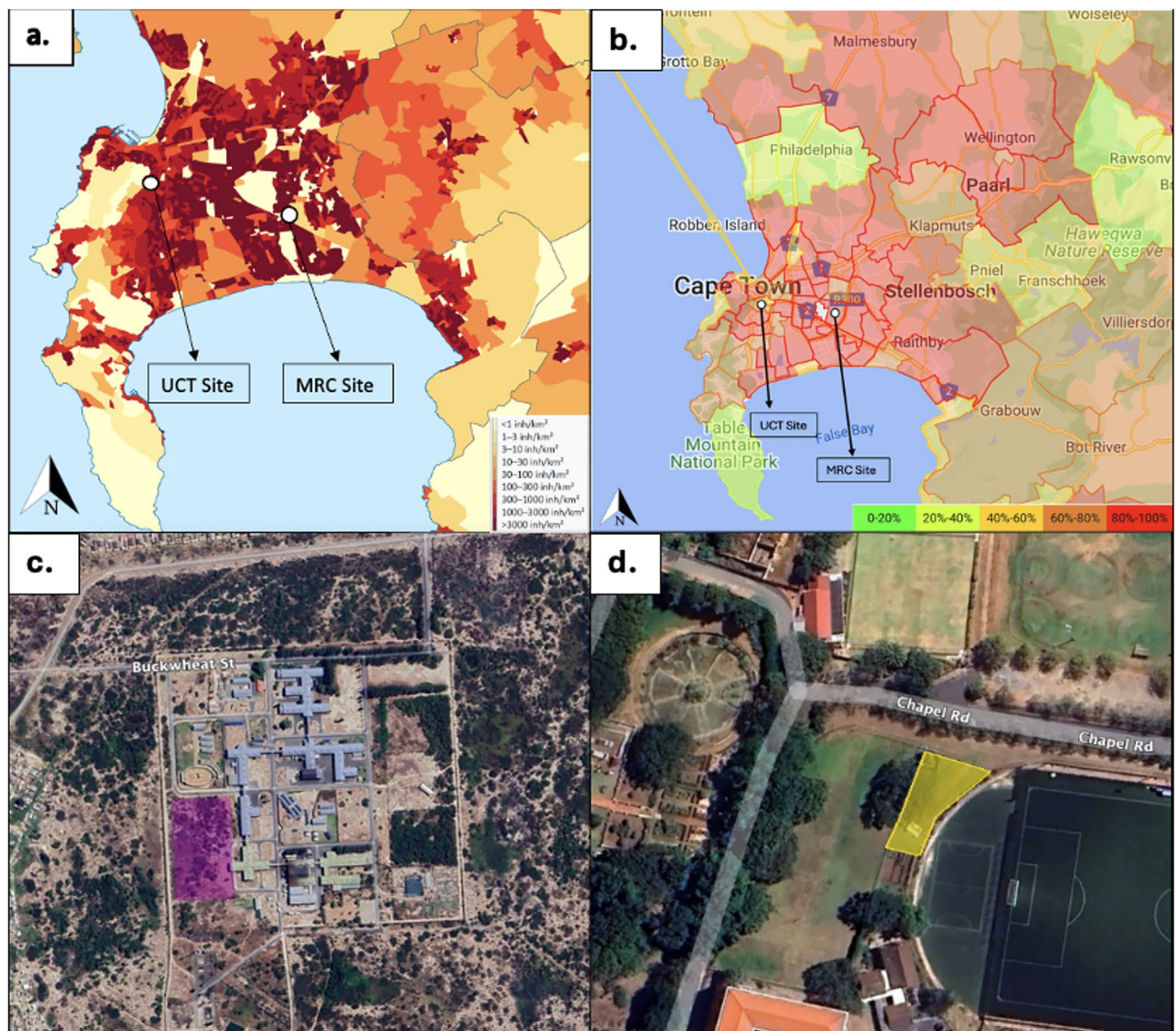


Figure 7. (a) Population density of Cape Town suburbs with the research sites indicated on the original map from the 2011 census at the “small area” level, 2015 (https://commons.wikimedia.org/wiki/File:Cape_Town_2011_population_density_map.svg) (b) Murder rate by suburb (2023) with research locations indicated on the original map from Crime statistics South Africa, (<http://www.crimestatssa.com>); the legend represents heat-mapping to show the quintiles of contact crimes (murders) in South Africa, where police precincts in the fifth quintile (top 20%) in terms of the numbers of murders nationally are indicated in red, (c) MRC research site located in Delft indicated on the map using Google Earth, (d) UCT research site located in Rosebank indicated on the map using Google Earth. This figure is modified from Adams et al. 2024.

Sample

Four 60 kg pigs (*Sus scrofa domestica*) were used as analogues for human bodies. The use of porcine bodies as proxies for humans in taphonomic studies where the establishment of baseline data are concerned is widely accepted within the scientific community^{37,38} and most taphonomic studies regularly use porcine bodies for human decomposition studies. We acknowledge that the results garnered from non-human animal models are not directly applicable to humans, and validation on human bodies or medico-legal cases is required. However, this does not diminish the value of baseline research conducted on animal models designed to develop and test methods and understand general patterns and ecological interactions as pertain to decomposition of large animal carrion. The four porcine bodies were deployed on January 13th 2022 (1 at UCT site & 1 at MRC site), July 1st 2022 (1 at UCT site), and January 13th 2023 (1 at UCT site), representing three summer and one winter deployment (the latter as a comparator). The animals were drawn from commercial stock (i.e., they were destined for human consumption, so their fate was not altered by the research) and were terminated by a single 0.22 caliber gunshot wound to the base of the brain. To ensure the animals’ welfare, this process was carried out by an industry professional, per the ethically approved protocol (FHS AEC 018_023). Following termination, within an hour of death, the bodies were lightly washed with water, and placed into body bags. Following the placement into

body bags, they were transported immediately to the two research sites without any refrigeration or freezing. In keeping with forensic realism, the bodies were deployed within two and a half hours of termination and clothed on site. Previous analysis of case files from the Forensic Anthropology Cape Town (FACT) laboratory by Spies³⁹ provided details regarding the most common clothing types for local medico-legal cases. The clothing used included: underwear, cotton T-shirt, denim pants, and a leather belt in the summer and the addition of socks, shoes, and jerseys in the winter^{39,40}. To ensure the accurate fit of clothing, alterations were made to accommodate the anatomical differences between humans and pigs. Spies³⁹ used measurements taken from a live 60 kg pig as a guide for tailoring the clothes: chest circumference was 87 cm; pelvis circumference was 81 cm; armpit height was 31 cm; shoulder height was 54 cm; groin height was 33 cm; thigh circumference was 45 cm; snout-to-tail length was 136 cm. Clothes were purchased in sizes to reflect these measurements and subsequently tailored accordingly.

Decomposition

Decomposition rate (by proxy of porcine body weight loss in kilograms over time) was determined using a solar-powered automated, remotely accessible taphonomic data collection apparatus^{15,16,41}. Once every 24-h period (at midnight), the scale would lift for 10 s, weight readings would be obtained, and each lift generated an email that was sent to the researcher listing the weight of the porcine bodies^{15,16,41,42}. Twenty readings were obtained during each lift and the average was used. The preference for weight loss over time was adopted as a more standardized approach for quantifying decomposition, particularly given variations such as the presence of clothing. Following the process laid out by Spies et al.⁴⁰ data collection was terminated when the body met at least one of the following criteria:

- (1) Skeletonization was reached if any one of or a combination of the following the criteria from Adlam and Simmons⁴³ are met:
 - A. Obvious loss of internal abdominal structure, spine only remaining under dried skin.
 - B. Substantial unweathered bone exposed (> 50%) and no wet decomposition when observed underneath.
 - C. Significant areas (> 30%) of bleached or weathered bone exposed.
- (2) The weekly accumulated weight loss drops below 5% of the original weight value for three consecutive weeks.

Desiccation sensor and data collection

Three PCB's were deployed in each body, and data from each PCB were transmitted via RS232 and collected via a RPi3B +, which assimilated and transmitted the information offsite. One PCB was deployed in each of the following areas on each porcine body: the head/neck, abdomen, and hindquarters regions of the porcine body (see Fig. 3). To ensure that the body was not prematurely purged, which might alter the rate and trajectory of decomposition given the published importance of the purge event^{44,45}, PCBs were only deployed post-bloat⁴¹. The PCBs were carefully inserted into the soft-tissue to avoid unnecessary trauma that could similarly potentially disrupt the natural decomposition process. These collected data were used to ascertain whether mummification in the Western Cape province adheres to a predictable pattern, to quantify the desiccation process, and to identify variables influencing moisture content.

Environmental variables

Temperature data were measured via the onsite weather station at each site (a Davis Vantage Pro 2) in degrees Celsius. Data were collected every fifteen minutes, and the minimum and maximum values were extracted and averaged for each day of data collection to calculate ADD. The weather station also recorded humidity data as a percent-age of relative humidity at the same frequency as temperature, solar radiation data were collected in units of $W\ m^{-2}$, and precipitation was recorded in millimeters. These weather data were used to calculate daily averages to provide more robust statistical analyses.

Statistical analyses

Generalized additive models were used to determine the driving environmental forces of desiccation, as this captures non-linear data. Tissue resistivity (as a proxy for tissue moisture content) was visually depicted using a scatterplot with ADD as the time scale. The data were bootstrapped to mitigate the impact of outliers and to assess the stability of our estimates. To enhance the accuracy of capturing the moisture loss curve, a LOWESS (locally weighted scatterplot smoothing) curve was incorporated into the scatterplot, as this allows for better visualization. Tissue resistivity was tested against the environmental predictor variables to determine the amount of variation they account for, and all of these were plotted against ADD. Predicted values of the region-specific tissue resistivity variables were measured for each porcine body.

Ethical approval

The research conducted for this study adhered to ethical guidelines and received approval from the relevant ethics committee. Specifically, the protocol was reviewed and approved by the Faculty of Health Sciences Animal Ethics Committee (FHS AEC) under the approval number FHS AEC 018_023.

Conclusions

The intricate understanding of late-stage decomposition and its correlation with the desiccation processes is fundamental for forensic taphonomists tasked with estimating the postmortem interval. The innovative approach presented involving the utilization of PCBs to quantitatively measure full-thickness soft-tissue desiccation simultaneously alongside a range of other variables utilizing automated data capture technology^{15,16} represents a significant advancement. By inserting PCBs into the decomposing porcine bodies, we were able to obtain continuous moisture readings at 15-min intervals, surpassing the limitations of previous methods that relied on less precise external measurements collected manually.

Through these daily measurements and quantitative analysis, this study illustrated notable desiccation variation among body regions and identified relative rates of desiccation. These results produce information on distinct desiccation trajectories observed between summer and winter decomposing bodies, with summer conditions notably conducive to desiccation and precocious natural mummification. Moreover, environmental factors, particularly temperature and solar radiation, emerged as significant drivers of tissue desiccation, overshadowing the influence of precipitation and humidity.

Furthermore, the creation of a measuring apparatus and systems for quantifying and analyzing soft-tissue desiccation at multiple depths is a significant milestone in forensic taphonomy. The creation of the PCBs and subsequent system of analysis to quantitatively measure desiccation through full soft-tissue thickness are a global first. This study represents the first quantitative analysis of desiccation deep tissue desiccation internationally, but also the first quantitative assessment of desiccation and natural precocious mummification in the Western Cape, South Africa. The exploration of desiccation as a potential indicator for estimating PMI opens new avenues for research, with implications spanning diverse fields. Beyond this, though, the real value of the present research lies in its demonstration of the value of integration of innovative methodologies and technologies, such as the use of PCBs, within a broader data collection framework that promises to revolutionize forensic taphonomic research and practices and enhance our understanding of postmortem processes, to the benefit of a wider range of disciplines.

Data availability

All data are available in the main text or the supplementary materials. The detailed technical designs of the PCB desiccation sensor are publicly available at the following Git Repository: JustinPead/temp_spike (github.com).

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Author contributions

Conceptualization: V.G.; D.F.; K.A.; J.P. Methodology: K.A.; D.F.; J.P. Investigation: K.A.; D.F.; V.G. Data curation: K.A.; V.G. Formal analysis: K.A.; D.F.; J.P. Writing—original draft: K.A. Writing—reviewing and editing: V.G.; D.F.; K.A.; J.P. Visualization: K.A. Supervision: V.G.; D.F. Funding acquisition: V.G.; D.F. Project administration: V.G.

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Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to V.E.G.

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