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ORIGINAL PAPER

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Developing a new scoring method to evaluate human decomposition in a humid, continental (Dfb) climate in Quebec

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Abstract

The published literature shows a lack of methods to evaluate the patterns and extent of decomposition of human remains and to estimate the post-mortem interval (PMI) in humid, continental (Dfb) climates such as Quebec. The aim of this study was to address this gap in the current knowledge base by providing the first observations from human corpses studied under controlled conditions in Quebec. A 12-month study was conducted at the site for Research in Experimental and Social Thanatology; the first human taphonomy facility in Canada. Six human donors with known time of death were deposited across spring ($n = 1$), summer ($n = 3$), and autumn ($n = 2$) 2021. The lack of suitability of the total body score method to evaluate the extent of decomposition at the facility prompted the development of a new scoring system based on the macromorphoscopic changes observed. The scoring system was applied to the donors to evaluate decomposition throughout seasons. All donors followed comparable decomposition trajectories, regardless of the season of deposition. Eighty-five percent of taphonomic patterns appeared in the first 25 experimental days or 5000 Kelvin accumulated degree days (350 ADD). Extensive desiccation of tissues was observed at a median of 21 experimental days across donors, resulting in a plateau within decomposition with no extensive skeletonization. To the authors' knowledge, this is the first published report of experimentally observed desiccation in such a form in a Dfb climate. This study provides new data on the types of decomposition patterns to expect in forensic investigations in southern Quebec and comparable climates.

KEYWORDS
desiccation, forensic taphonomy, scoring system, soft tissues, South-eastern Canada, terrestrial decomposition

Highlights

- The decomposition of six donors was monitored over 12 months in spring, summer, and autumn.
- A new scoring system was developed to document the taphonomic patterns observed on the donors. Eighty-five percent of taphonomic patterns appeared within 25 days (5000 KADD/350 ADD) regardless of the season.
- Extensive desiccation of the tissues was observed in all donors, resulting in arrested decay.
- This is the first report of extensive desiccation in Quebec and in a Dfb climate more generally.

1 | INTRODUCTION

In forensic investigations involving human remains, forensic taphonomy offers valuable insights to reconstruct the circumstances surrounding death and the sequence of events until the recovery of the remains [1–3]. Furthermore, investigating forensic taphonomy, including human decomposition, is essential in forensic contexts because decomposition processes can destroy, obscure or mimic evidence of criminal activity [4–6]. Decomposition processes can serve as evidence in their own right in forensic investigations [7, 8]. In recent years, the truly interdisciplinary nature of forensic taphonomy is becoming more and more acknowledged [9, 10], thus potentially migrating towards a more 'standalone' field of research, and not necessarily as part of a parent discipline such as forensic anthropology.

After death, human tissues undergo various macromorphoscopic changes over time (referred to as 'taphonomic patterns'), which are the focus of the present study. Several methods have been developed to characterize macromorphoscopic taphonomic patterns and use them to estimate PMI. One of these methods was developed by Megyesi et al. [11], derived from Galloway [12]. This scoring method is based on the principle of Total Body Score (TBS) in which the overall extent of decomposition of the body is evaluated through the visual observation of three body regions; head–neck, trunk, and limbs (upper and lower). The Megyesi et al. [11] method is a key reference in forensic taphonomy and has been applied to and/or adapted to various environments and forensic scenarios [13–16]. TBS approaches are non-invasive, portable, inexpensive, and user-friendly [17]. However, their reliability is influenced by several variables linked with the methodology, the experimental conditions, and the environment considered, all of which may compromise the accuracy of decomposition measurements and PMI estimation [18–23].

The decomposition process is a complex continuum, rather than a unique event, that encompasses several stages of degradation that follow each other in a time-related manner [2, 24–26]. There is great variability in the rates and patterns of decomposition depending on a combination of endogenous factors (e.g., body mass, medication, illicit drug intakes, presence of perimortem trauma, exsanguination around time of death, etc.) and exogenous factors (e.g., climate, temperature, ambient humidity, presence of insects, thanatomicrobiome, soil moisture, soil pH, altitude, etc.) [27–31]. Under certain conditions, decomposition can be slowed down or even 'halted', including due to freezing, desiccation and/or adipocere [10, 12, 25, 32–37]. These phenomena yield an overall preservation of the remains which may introduce uncertainty in the evaluation of the extent of decomposition and the estimation of PMI. In these scenarios where decomposition diverges from an 'expected' decomposition trajectory, there is a lack of consensus on the timings of appearance, duration, and disappearance of macroscopic taphonomic patterns depending on the environment considered [25]. Overall, these variations in the taphonomic processes—what Wescott [38] refers to as 'the unpredictability'—may result in uncertainty in the forensic taphonomic conclusions.

Despite the valuable contributions of retrospective studies on large sample sizes [35, 39] to the advancement of forensic taphonomy, there is a clear need for more experimental studies on human donors in controlled conditions [25]. Human remains decomposing in arid climates [12] or subtropical climates, where many ($n = 6$) human taphonomy facilities in the USA are currently located, may present postmortem changes different from more continental climates. A survey of the literature highlighted a lack of methods to evaluate the extent of decomposition of human remains and to estimate PMI based in humid, continental (Dfb) climates such as Quebec [40]. One of the few recent publications available on human decomposition in Canada [39] is based on a retrospective study of medicolegal cases across the country but not on human corpses studied under controlled conditions. Additionally, in situ observations of human donors over 12 months at the human facility in Quebec (Canada) underlined the lack of suitability of the taphonomic methods that are currently available for human remains in Quebec, an issue also outlined by Cockle and Bell [39].

To address this gap in the current knowledge base, the present study aimed to characterize macromorphoscopic postmortem changes and their timings of appearance in southern Quebec with a new scoring method. The research was carried out on human donors at the facility for Research in Experimental and Social Thanatology/*Recherche en Sciences Thanatologiques [Expérimentales et Sociales]*, herein referred to as REST[ES]. REST[ES] is the first human taphonomy facility in Canada to date, thereby offering the opportunity to conduct rigorous experimental studies on human donors in a way that was not possible before, as noted by Cockle and Bell [39] in 2017 before the REST[ES] facility was opened. Human donors provide more realistic models for human decomposition in forensic scenarios than non-human mammal models such as pigs (*Sus scrofa domesticus*) that are often used in experimental studies [41, 42]. In this one-year study we report what we believe to be representative taphonomic patterns and their timing of appearance throughout the decomposition process in the spring, summer, and autumn months. A new scoring system supported by a color photographic atlas was developed to categorically describe the trajectory of gross postmortem changes at the REST[ES] facility. The new scoring system intends to complement the forensic researchers' and practitioners' toolkits to evaluate the extent of decomposition and assist with the identification of unidentified human remains in forensic investigations. This study provides the first comprehensive record of human taphonomy in an experimental setting in a Dfb climate.

2 | MATERIALS AND METHODS

2.1 | Human donors at the REST[ES] facility

The REST[ES] facility is located in Bécancour (N 46.3473, W 72.4179), a semi-rural area in Centre-du-Québec region, on land owned by the Industrial Parc and Port of Bécancour (*Société du Parc*

Industriel et Portuaire de Bécancour). REST[ES] is a 1600 sqm highly secured site (CCTV cameras, electric fences, barbed wire) to protect the integrity and privacy of the donors. The vegetation at the site is mixed woodland and dominated by red maple (*Acer rubrum* L.) and white spruce (*Picea glauca*) trees. The facility has loamy sand A and B soil horizons, with sandy soil at the surface and loamy soil at deeper sub-surface levels. The site was chosen as it represents a typical environment in which local police services may be deployed to search for and recover human remains [43].

The bodies of six adult donors donated through the Université du Québec à Trois-Rivières (UQTR) Body Donation Program were analyzed in this study (Table 1). The selection of donors consisted of 4 males and 2 females, ranging from 54 to 93 years old. The cause of death, time of death, and time of deposition at the REST[ES] facility was known for all donors. The bodies of all donors were kept refrigerated (4°C) at the morgue within the UQTR Anatomy Laboratory for approx. 24 h prior to being placed at the REST[ES] facility. The bodies of the donors were all prepared at the laboratory prior to placement at the site. Preparation included removing clothing, cleaning the body with ethyl alcohol 70%, and placing a plastic identification tag around the toe. When present, dentures, medical devices, and implants were left within the donors. The donors' corpses were all deposited undressed, in a supine position, on the soil surface at the REST[ES] facility. All corpses were protected by wire meshed cages to limit vertebrate animal scavenging and associated risks of scattering of the remains [44, 45], whilst allowing invertebrate activity which is known to be a driver in the decomposition process [18, 46]. Further details on entomological communities and vertebrate scavengers at the REST[ES] facility can be found in previously published studies, including pilot studies analyzing non-human mammal models (*Sus scrofa domesticus*) [43, 47, 48]. In the present study, the donors were deposited at the REST[ES] facility at different times of the year to observe the effects of seasonality on the decomposition processes, and were therefore subject to different weather conditions (Table 1, column 'Season of arrival at REST[ES]').

2.2 | Data collection

In situ real time observations were collected from the donors over a 12-month period, from May 2021 to May 2022. This approach enabled us to place donors in three seasons (i.e., spring, summer, and autumn) and collect data across all four seasons (including winter) in the southern Quebec climate. Visual examinations of the donors and scoring of the extent of decomposition were performed on a daily basis in the first 20 days following the deposition of each donor at the REST[ES] facility, then once every 2 days when a decrease in the speed of external postmortem changes was observed, then once a week or once a month when no significant changes were observed. The longitudinal approach taken with regular monitoring of the donors facilitated the identification of the timings of appearance, duration, and potential disappearance of various taphonomic patterns over the course of decomposition. Digital photographs were collected as previous studies showed their value to evaluate the extent of decomposition of human remains with high inter-observer reproducibility [21, 22, 25]. A standardized protocol (Table 2) was developed to maximize photographic coverage of the body and reproducibility of the photographs, as advised in Ribéreau-Gayon et al. [22].

2.3 | Weather data

Data for ambient temperature (°C), precipitation (mm), relative humidity (%), solar radiation (W/m^2), speed (m/s), and direction of wind were collected every 15 min using a weather station equipped with a data logger (HOBO U30 No Remote Communication, Onset Computer Corporation, Bourne, MA, USA) placed within the REST[ES] facility. Only ambient temperature was considered in the present study which is designed as a baseline study. To account for the various season of deposition of the donors at the REST[ES] facility, accumulated degree days (ADD) were calculated for each donor using a base temperature of 0.0°C [11, 49]. Kelvin accumulated degree days (KADD) were also computed following Dabbs and Martin [50] as this approach enables to more accurately account for sub-zero temperatures that are encountered at the REST[ES] facility. KADD also help standardize taphonomic patterns for other taphonomy facilities to facilitate comparisons across various environments. For these reasons, only KADD are presented in the figures included in this study. KADD were calculated by averaging the daily maximum and minimum temperatures in K and adding for each chronological day. All analyses and graphs were produced with GraphPad Prism version 9.4.0 for Windows (GraphPad Software, San Diego, California, USA, www.graphpad.com).

2.4 | Developing a new scoring system to evaluating human decomposition

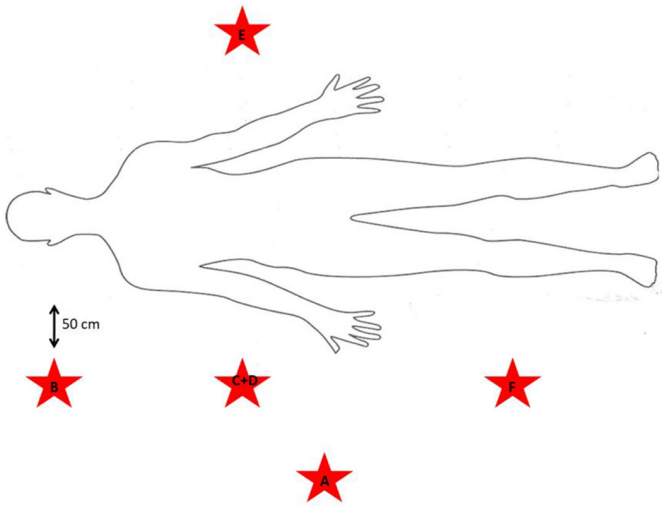
The Megyesi et al. [11] method was first applied to five donors deployed at the REST[ES] facility between August and November 2020 (not included in this study). The need for a novel scoring method was identified during the early stages of the study. It was first observed that after the earliest stages of decomposition, existing methods were not suitable, especially as the donors displayed taphonomic patterns that were not included in the Megyesi et al. [11] scoring system (e.g. moist and shiny appearance of the exposed dermis, desiccation of tissues, etc.). Comparable issues linked with applying the Megyesi et al. [11] scoring system in cases showing desiccation were also raised by Connor et al. [25] and Ceciliason et al. [35]. This issue highlighted the lack of suitability of existing taphonomic methods to the REST[ES] facility and thus formed the basis for developing a new scoring system to evaluate human decomposition that is adapted to the southern Quebec environment and potentially other Dfb climates more broadly.

TABLE 1 Data available on the donors ($n = 6$) analyzed in the present study at the REST[ES] facility. The table presents the personal, demographic, and medical data available for the six donors included in the study. Various levels of details on medication and pathological conditions were available to us, depending on the data provided by the donors or their relatives through the UQTR Body Donation Program

Donor ID	Date & time of death	Date & time of arrival at anatomy laboratory	Date & time of arrival at REST[ES]	Season of arrival at REST[ES]	Age	Sex	Weight (kg)	Height (cm)	BMI	Cause of death	Medical records	Medication
1	10 May 2021 at 01:00 a.m.	10 May 2021 at 4:30 p.m.	11 May 2021 at 11:00 a.m.	Spring	77	M	79.5	177	25.2	Stage 4 Metastatic melanoma in lungs, brain, bones, muscles, kidneys, adrenal glands, and liver	Not available	Not available
2	21 June 2021 at 07:35 p.m.	21 June 2021 at 7:37 p.m.	23 June 2021 *(Time not available)*	Summer	91	M	80	170	27.6	Metastatic cancer in lungs and prostate	Metastatic lung cancer	Not available
3	09 July 2021 at 07:00 p.m.	09 July at 12:36 p.m.	10 July 2021 at 02:30 p.m.	Summer	93	F	60	153	25.6	Likely thrombosis in lower limb, dementia	Ovarian cancer (1954)	Synthroid and sleep medication
4	30 July 2021 at 08:00 a.m.	30 July 2021 at 9:30 a.m.	01 August 2021 at 10:10 a.m.	Summer	72	F	65.7	155	27.8	Malignant arrhythmia	Not available	Pregabalin, Mylan-nitro
5	30 September 2021 at 08:30 p.m.	01 October 2021 at 8:30 p.m.	02 October 2021 at 11:45 a.m.	Autumn	78	M	56	185	16.3	Advanced lung neoplasia (tumor)	Not available	Not available
6	11 October 2021 at 8:30 a.m.	11 October 2021 at 5:00 p.m.	12 October 2021 at 11:00 a.m.	Autumn	54	M	44	163	16.5	Metastatic lung cancer	Not available	Not available
Median demographic data:					77.5		62.9	166.5	25.4			

TABLE 2 Photography protocol developed at the REST[ES] facility. Standardized photographic documentation with six photographs that capture the body for both left and right sides and a bird's eye view

Steps	Actions	
Step 1	Photograph tag with donor ID	
Step 2	Photograph top of the scoring sheet with date and experimental day (ED)	
Step 3	Stand on the right side of the donor, about 50 cm away from donor, as shown in the diagram below.	
Step 4	Take the following photographs (A–G) by moving along an imaginary line, parallel to the donor:	A. Whole corpse (head to toe) from bird's eye view *Advice: Take the photograph horizontal to the body, with camera pointing towards lower abdomen/pubic region.* B. Head–neck from bird's eye view C. Trunk (thorax + abdomen) from bird's eye view D. Right arm (from shoulder to finger tips) from bird's eye view E. Left arm from bird's eye view *Advice: After photographing left arm, return to the right side of the donor, about 50 cm away.* F. Lower limbs (from genitalia to toes) from bird's eye view G. Close ups: any details of interest from the angles most relevant, after placing a 10 cm scale close to the corpse and in the same plane as the corpse/area of interest. *Advice: Regardless of the location of the details of interest, always take photographs A to F first before going back to any details to ensure standardization.*



A new scoring system was developed (Table 3) based on the visual examination of the five donors mentioned above who were not included in the present study but whose photographs were included in the scoring system as a visual aid. The scoring system was then refined based on the observation of a selection of six other donors deployed at the REST[ES] facility between May and October 2021 (Table 1). The scoring system categorically describes the trajectory of gross external postmortem changes at the REST[ES] facility. It comprises 28 macromorphoscopic taphonomic patterns than can be observed visually at any given location within the body, without distinction of anatomic region. The user of the scoring system writes '1' in the far-right column ('Patterns observed') every time they are able to observe the corresponding taphonomic patterns, using the descriptions of the patterns and the photographs as a visual aid (Table 3 and associated Figures S1–S28 available as Supplemental Information). The total number (*n*) of patterns observed (bottom row in Table 3) therefore reflects the variety and diversity of taphonomic patterns over time for each donor. The literature on human taphonomy—both in terrestrial and aquatic environments—has traditionally been using quantitative scoring systems that are inversely proportional to the progression of decomposition over time so that the fresher the body the lower the score, and the more decomposed the body the higher the score [11, 12]. In this study, we sought to develop a scoring system that is proportionate to the decomposition process, with the Total *n* taphonomic patterns observed decreasing as decomposition slows down or enters a plateau phase, and the appearance of new taphonomic patterns becomes rarer. Additionally, the scoring system was designed to account for simultaneous taphonomic patterns at given points in time whereas traditional taphonomic methods, such as Megyesi et al. [11], used fixed decomposition categories that tend to be mutually exclusive, an issue also raised by other studies [15]. In the scoring method we developed, scoring simply refers to the

TABLE 3 Macromorphoscopic scoring system developed at the REST[ES] facility. Associated photographs (Figures S1–S28) are available as Supplemental Information. The table presents the categorical scoring system developed to evaluate the extent of decomposition of the donors and the taphonomic patterns observed at the REST[ES] facility. Images as visual aids to illustrate the taphonomic patterns are available as Supplemental Information

Taphonomic patterns	Descriptions	Photographs	Patterns observed
Fresh	No visible changes	Figure S1	
Discolouration within the tissue	Intrinsic phenomena, including lividities and marbling	Figure S2a,b	
Goose bumps	Small bumps on skin (i.e., 'plucked chicken skin')	Figure S3	
Blistering of skin	Bubble(s) underneath most superficial layers of skin (epidermis)	Figure S4	
Skin slippage	Ongoing slippage of most superficial layers of skin (epidermis)	Figure S5	
Bloating	Swelling of body parts including face (e.g., eyes protruding, mouth, nose, cheeks), trunk (e.g., breast, abdomen, genitalia), and limbs	Figure S6	
Defined areas of dry tissues	Isolated patches of dry skin (dermis) surrounded by fresher looking dermis	Figure S7	
Dermis exposed showing a moist shiny appearance	Epidermis has fallen off leaving underlying layers of skin (dermis) exposed with a moist shiny appearance, potentially linked with sunlight exposure	Figure S8	
Dermis exposed showing a dry matte appearance	After epidermis has slipped off, leaving the dermis exposed but before reaching further desiccation which would be characterized as 'Dry tissues with no bone exposure' further below	Figure S9	
Tissues showing a rehydrated appearance	Washed out appearance after rainfall (typically a white or gray moist appearance)	Figure S10	
Small pitting on skin	Small punctures in tissue, the diameter of a toothpick, likely caused by larval activity	Figure S11	
Hair fallen out	Majority of head hair has fallen out and is laying on the ground (not embedded in tissue). Small thin head and body hair may remain	Figure S12	
Nails fallen out	Majority of the fingernails and toenails not embedded in tissue	Figure S13	
Liquefied tissues	Melting appearance of tissues: viscous, wet, associated with strong odor	Figure S14	
Cadaver decomposition island	Wet soil around body due to release of decomposition fluids (typically a dark silhouette)	Figure S15	
Wrinkly dry tissues	Slight crinkled appearance of tissues (dermis)	Figure S16	
Heavily wrinkled dry tissues	Pronounced crinkled appearance of tissues (dermis) forming parallel billows separated by grooves. Can take the form of wood-like appearance in most pronounced forms.	Figure S17	
Defect in tissues	Defined holes larger than pitting, potentially associated with larval activity	Figure S18	
Tendon exposure	Filaments attached to bones and tissues (resulting from liquefied muscles)	Figure S19	
Outlines of bones and/or joints visible due to desiccation	Bone structure clearly defined below desiccated tissue (e.g., shoulders, sternum, rib cage, hips, knees, etc.)	Figure S20	
Dry tissues with no bone exposure	Overall desiccated body with no bone exposure	Figure S21	
Predominantly dry or moist tissues with minimal bone exposure	Partial bone exposure in one or several body regions (e.g., face, throat, hands, pelvis, tibiae). In these regions, skeletonization can be extensive exposing most of the visible bone structure but considered as a whole, the body is skeletonized to less than half of its visible surface	Figure S22	
Teeth fallen out and/or denture if relevant	Teeth and/or denture not embedded in alveolar bone (mandible and/or maxilla)	Figure S23	
Discolored patches on the skin	Extrinsic phenomena (e.g., lichens, fungi, etc.)	Figure S24	
Areas of liquefied or re-solidified fat and/or adipocere	Fat (adipose) tissues show a liquefied or re-solidified appearance and/or presence of adipocere (or saponification)	Figure S25	

TABLE 3 (Continued)

Taphonomic patterns	Descriptions	Photographs	Patterns observed
Majority of bones exposed with some dry tissues remaining	More than half of the visible surface of the body is skeletonized	Figure S26	
Complete skeletonization with anatomical connections	The bones of a joint remain connected to one another although articulation can be loose	Figure S27	
Complete skeletonization with disarticulation	The bones of a joint are not connected to one another: no anatomical connection remains	Figure S28	
Total *n* taphonomic patterns observed:			

adding of scores corresponding to the taphonomic patterns that were observed. The scoring system developed is therefore categoric and not a quantitative approach per se. This approach was chosen as it reflects the variety and diversity of taphonomic patterns over time, which enables one to document differential decomposition within a single body (see Figure S11 for example), as also suggested by Alfsdotter and Petaros [15]. To our knowledge, this study is the first to propose a scoring system of this kind. The new scoring system does not include color-based descriptions, as often found in taphonomic methods [11, 14, 51], in order to reduce bias in the evaluation of decomposition (e.g., lividities may be difficult to observe on the most pigmented dark skins [16, 22]) and to standardize the application of the scoring system in various lighting conditions and seasons, and by different users [22].

The new scoring system was then applied to the six donors by the first author of this paper (ARG), in a comparable approach to that taken by Cockle and Bell [39]. Total n of taphonomic patterns observed per donor was not reported in this study as it followed a comparable trajectory to that of the timing of appearance of the taphonomic patterns (presented in the Results section) and thus offered comparable insights into the decomposition processes at the REST[ES] facility. The pattern 'Tissues showing a rehydrated appearance' (Table 3) was removed from subsequent analysis as this pattern appears to be weather dependant (i.e., linked with rainfalls) and not directly linked with intrinsic biological activity. It is nonetheless a pattern worth documenting as it was observed repeatedly at the REST[ES] facility.

3 | RESULTS

Overall, all six donors followed comparable decomposition trajectories, regardless of season of placement (Figure 1A). Gross decomposition progressed as follows: Fresh—Discolouration within the tissue (livor mortis and venous marbling) and Goose bumps—Blistering—Skin slippage—Bloat—Exposed dermis showing a moist shiny appearance and/or a dry matte appearance—Desiccation. The majority (95%) of the taphonomic patterns were observed within the first 52 experimental day (ED), regardless of season of placement. A peak in terms of diversity of patterns within the first 25 ED (Figure 1B) was noted whereby 85% of the taphonomic patterns were observed (data not presented but available upon request). After 52 ED post deposition, a plateau phase was reached for all donors, where no new taphonomic pattern was observed which is evidenced by a decrease in the number of data points in Figure 1. That trend was observed in both the spring–summer (Donors 1, 2, 3, and 4) and autumn donors (Donors 5 and 6). The decomposition trajectories of the six donors considered in KADD followed a comparable trend to that observed in ED regardless of the season the donors were placed (Figure 2). The majority of the taphonomic patterns were first observed within the first 5000 KADD (350 ADD; data not shown) followed by a plateau phase in the decomposition trajectory. A trend towards differential decomposition was observed in all donors, as shown in Figure 2 with several taphonomic patterns appearing simultaneously on a single donor. Winter data were not included in this study however future studies will investigate the impact of humidity and snow fall on the decomposition trajectories at the REST[ES] facility.

In the 'early postmortem period' (i.e., before signs of desiccation), the decomposition trajectories observed at the REST[ES] facility were overall comparable to those reported in the literature, until bloat. However, defined areas of dry tissues were observed as the body had not started bloating yet, between 2 and 7 ED, with a median at 5 ED across all donors or between 584.5 and 2056.7 KADD (38.2–125.8 ADD), with a median at 1448 KADD (58.3 ADD) (Figure 2; ADD data not presented but available upon request). Bloating was first observed between 7 and 14 ED, with a median at 9 ED across all donors except Donor 6 who displayed mild abdominal bloat at the time he arrived at the REST[ES] facility (on Day 1) and can be considered an outlier in that regard (Figure 1A). The decomposition trajectory differed substantially from 'typical decomposition' when 'Wrinkly' and 'Heavily wrinkled' tissues were observed which indicated that the body transitioned into desiccation. Signs of desiccation (n = 3) at the REST[ES] facility were first observed between 7 and 58 ED (Table 4). Desiccated tissues formed a kind of shell over the body which prevented external decomposition and extensive bone exposure overall. Only minimal bone exposure was observed across the six donors, mostly located in the anterior surfaces of the head–neck, wrist-hand, and lower abdomen-pelvic regions. By preserving the tissues, desiccation also caused certain taphonomic patterns to become protracted

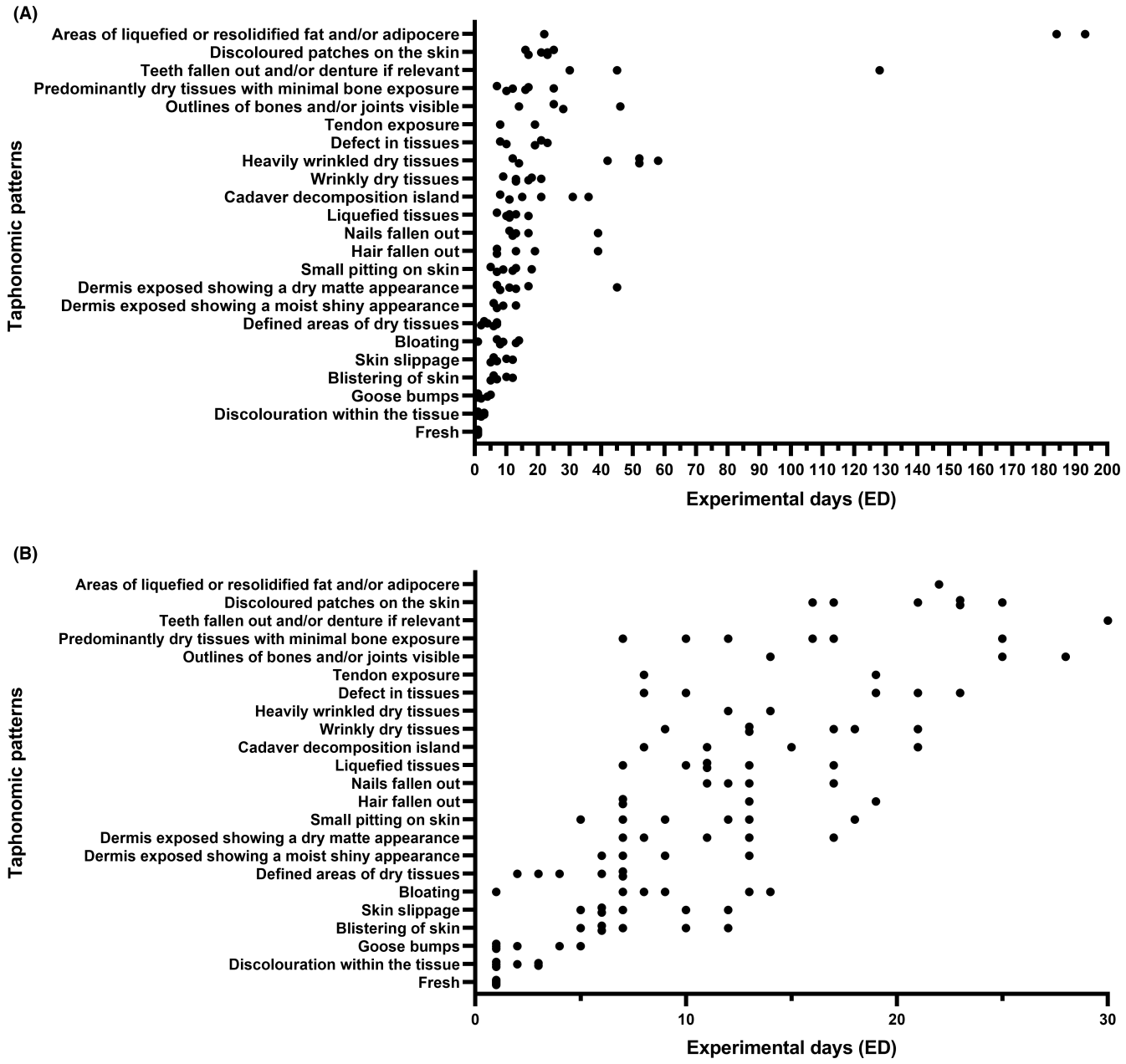


FIGURE 1 Timing of observation of taphonomic patterns in the six donors over the course of the study, organized by experimental day (ED). (A) Timing of observation of taphonomic patterns in the first 200 ED. (B) Timing of observation of taphonomic patterns in the first 30 ED. (A and B) Each point represents the first time a given pattern was observed in a donor ($n = 6$) over the course of the study. Only the most frequently observed taphonomic patterns (23 out of 28) are reported in the graph for ease of interpretation. For example, 'Complete skeletonization with anatomical connections' and 'with disarticulation' are not presented as they were not observed in the present study, however it is important that these patterns are included in the scoring system (Table 3) as they may be encountered in the future at the REST[ES] facility or by other research groups wishing to apply and/or adapt the scoring system to their local environment. (a) The graph shows the chronological succession of taphonomic patterns across the six donors over 200 ED. ED 1 represents the day of deployment of the donor at the REST[ES] facility. The number of points decreases from 25 ED onwards indicating that few taphonomic patterns appeared from that point onwards in the decomposition process. This plateau phase indicates that decomposition has slowed down or 'halted'. This phenomenon is shown in more detail in (B). (B) The graph is derived from (A) and focusses on the first 30 ED. It shows the diversity of taphonomic patterns encountered in this timeframe across all six donors, and their succession over time. It further highlights the simultaneity of most taphonomic patterns across the donors regardless of the season in which they were deposited at the REST[ES] facility.

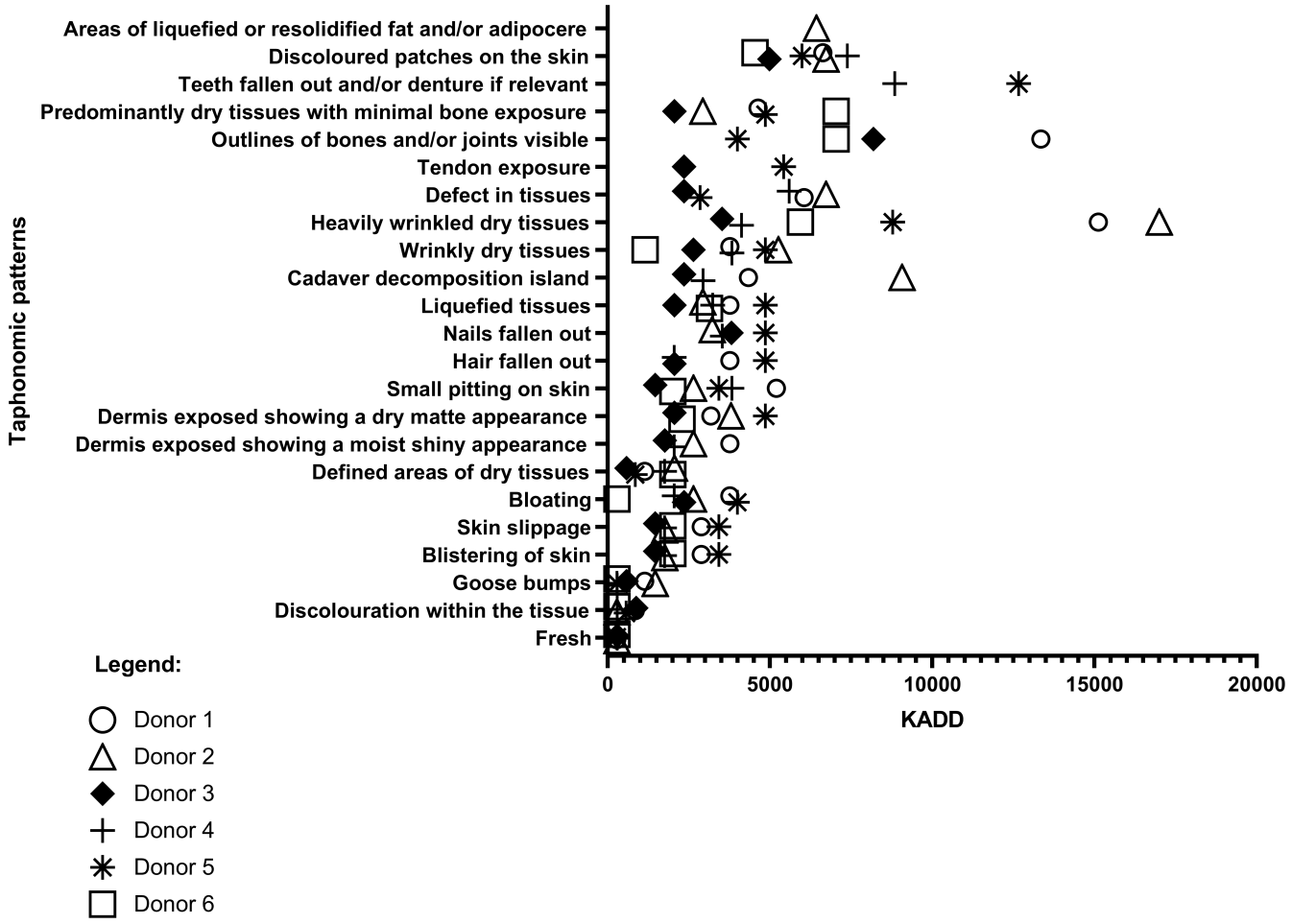


FIGURE 2 Timing of observation of taphonomic patterns in KADD in the six donors over the course of the study. Each symbol represents the first time a given pattern was observed in one of the six donors over 20,000 KADD. Only the most frequently observed taphonomic patterns (23 out of 28) are reported in the graph for ease of interpretation, similar to Figure 1. The graph shows that most taphonomic patterns were first observed under 5000 KADD (350 ADD; data not shown), followed by a plateau phase, regardless of the season in which the donors were placed. It further shows the simultaneity of certain taphonomic patterns within a single donor which indicates a clear trend towards differential decomposition.

TABLE 4 Typical taphonomic patterns of desiccation at the REST[ES] facility and their timing of first observation on the six donors

	Timing of 1st observation (ED)[a]	
Patterns of desiccation	Range	Median
Predominantly dry tissues with minimal bone exposure	7–25	14
Outlines of bones and/or joints visible	14–46	27
Heavily wrinkled skin	12–58	47
Combined signs of desiccation[a]	7–58	21

[a]Calculated across the six donors.

beyond their initial timing of appearance (within the first 25 ED for the majority) as they remained visible later in the decomposition process, such as discolouration within tissues (i.e., venous marbling) and skin slippage.

4 | DISCUSSION

4.1 | General decomposition trajectory at the REST[ES] facility

The new scoring system developed in this study enabled detailed documentation of the taphonomic patterns at the REST[ES] taphonomy facility and a deeper understanding of the sequence of decomposition in southern Quebec. For some of the taphonomic patterns observed it was possible to identify a period of onset, duration, and disappearance (e.g. 'Fresh' and 'Discolouration within tissues') but others (e.g., 'Dry tissue with no bone exposure' and 'Predominantly dry tissue with minimal bone exposure') are still ongoing at the time of reporting these findings. Future longer-term studies will analyze the patterns of skeletonization at REST[ES] in more detail. While some taphonomic patterns had a clear timing of occurrence with 'short' durations, others are likely to occur at a later stage within the decomposition process and last for longer periods of time. As such,

these two main categories of patterns may have the potential to indicate whether the remains are more likely to be within relatively 'shorter PMIs' (≤25 days) or 'longer PMIs' (>25 days). These indicators within the decomposition process could constitute a helpful triage phase in the midst of a forensic investigation involving human remains [10].

4.2 | Desiccation of tissues

This study showed that extensive desiccation of tissues at the REST[ES] facility caused arrested decay [52] which persisted for several months and is still visible at the time of writing. After collecting a year of in situ data, desiccation can be considered typical from the decomposition trajectory for our site and microclimate. Three external signs were identified as representative of desiccation at the REST[ES] facility (Table 4): 'Predominantly dry tissues with minimal bone exposure' (see Figure S22), 'Outlines of bones and/or joints visible' (see Figure S20), and 'Heavily wrinkled skin' (see Figure S17), by order of appearance on the bodies across all donors included in this study. Such findings are important to report as it can help investigators better understand the levels of preservation of human remains to search for/expect in forensic scenarios to maximize successful search, recovery, and positive identification of unidentified remains. It must however be noted that vertebrate scavenging was prevented at the REST[ES] facility and as such, the taphonomic patterns reported in this study may not be typical of all forensic investigations, particularly those involving scavenging [45, 53]. Desiccation of the donors prevented extensive skeletonization. At the time of writing, none of the donors included in this study have fully skeletonized after ≥365 days post deposition (Donors 1, 2, 3, and 4) and >182 days (Donors 5 and 6). Comparable trends in plateaued decomposition with limited bone exposure due to desiccation have been reported in Canada (Quebec not included) [39], Sweden [15], Colorado [25], Arizona [12], and Australia [11, 44, 54]. For example, Cockle and Bell [39] noted that no body in their forensic dataset was fully skeletonized in under 1 year and that only eight cases showed >50% skeletonization, and Connor et al. [25] reported that skeletonization >50% was rare among their donors even after 1000 days postmortem (approx. 3 years). Furthermore, a forensic outdoor case in a comparable Dfb climate in Sweden [15] did not show any bone exposure at a PMI of 148 days (645 ADD) during the colder months. Although the latter studies were conducted in climates that are different from the REST[ES] facility: their findings in conjunction to those of the present study highlight a taphonomic trend towards desiccation of remains in various environments that southern Quebec had not necessarily been associated with to date.

Generally, desiccation results from the dehydration of soft tissues in which the external layers of tissues become discolored, hardened, and dried, potentially with a leathery appearance, associated with overall shrinkage of the body [12]. This phenomenon is attributed to dry, well aerated environmental conditions as they facilitate rapid drying of soft tissues thereby limiting putrefaction which would otherwise lead to moist—or even liquefied—tissues [12, 37, 55–57]. While desiccation of human remains in arid environments—hot or cold/glacial—has been well described [12, 36, 54, 55, 58, 59], reports of cases of desiccation in temperate [52, 60, 61] and humid environments [25, 35] are scarce. In contrast to the present study, the retrospective study conducted by Cockle and Bell [39] across various provinces in Canada—although none from Quebec—did not find any case of extensive desiccation. In that study, desiccation was limited to fingertips and/or face only which was observed on average at a PMI of 75 days in the spring–summer and 58 days in the autumn-winter whilst in our study first signs of desiccation were observed approx. 4–5.5 times earlier, considering the median of the six donors. The differences between the findings may be explained in part by climatic differences across Canadian provinces and the fact that in the Cockle and Bell [39] study the bodies were recovered from outdoor environments where they may have been subject to vertebrate animal scavenging, which was restricted in our study. However, recent experimental studies in Western Colorado (hot summer continental Dfa climate) [25] and New South Wales in Australia (humid subtropical Cfa climate) [44, 62] have reported cases of extensive desiccation which macromorphoscopic patterns and timings of appearance are consistent with our findings. The patterns of desiccation described by Connor et al. [25] in Colorado are comparable to those observed at our facility, including 'definition of patellae' (included in our definition of 'Outlines of bones and/or joints visible [...]'; see Figure S20) and 'crenulated' tissues (which we referred to as 'Heavily wrinkled dry tissues with wood-like appearance'; see Figure S17). Furthermore, the first signs of desiccation reported by Knobel et al. [44]—10 ED in the summer and at 16 to 20 ED in the winter in Australia—fit within the range of our present findings.

The mechanisms that led to extensive desiccation of the donors in the present study may result from a combination of exogenous and endogenous factors. In terms of exogenous factors, the sandy soil at the REST[ES] facility may have played a role in the desiccation of the remains as it appears that sandy soils with low moisture content promote desiccation [37, 57]. This phenomenon is likely related to the high rate of gas diffusivity of coarse textured soil, which enables moisture and gases to rapidly percolate through the soil matrix [63]. With regards to endogenous taphonomic factors, little is known about how they affect decomposition. The impact of diseases and medication is merely mentioned in the studies available [30], which are often lacking references, large study datasets or experimental approaches on human donors in controlled conditions. In the present study, four (67%) of the six donors died of cancer and one (Donor 3) had cancer ante-mortem (Table 1). The prevalence of cancer in the selection of donors is representative of all the donors deposited at the REST[ES] facility at the time of writing (n = 16) where 62.5% had cancer ante-mortem and/or peri-mortem. Information on potential chemotherapy and radiotherapy in the selection of donors was not available to us. The only donor (Donor 4) who did not have cancer according to the records available followed a similar decomposition trajectory to that of the other donors in the study,

characterized by extensive desiccation. The case of that donor indicates that desiccation can occur in the absence of cancer and associated treatment protocols which suggests that the local environmental conditions play a critical role in this process at the REST[ES] facility. Generally, it is likely the interconnectedness of some endogenous factors, such as medical treatments, with certain exogenous factors can impact the rates and patterns of decomposition. The present baseline study focused on the analysis of the impact of temperature, which has been shown to be a driver of decomposition [27, 49]. Future studies will further investigate the impact of exogenous and endogenous taphonomic factors to develop a more comprehensive understanding of human decomposition trajectories at the REST[ES] facility.

4.3 | Building a baseline for forensic taphonomy in Quebec

The frequencies at which the taphonomic patterns presented here were observed at the REST[ES] facility show their relevance as indicators of the decomposition process at our site and thus outline the importance of recognizing and including them in future studies on human taphonomy in Dfb climates. Furthermore, the new scoring system developed in this study represents an important first step towards overcoming some of the limitations linked with traditional taphonomic methods, including by offering a visual assessment tool that is not reliant on color descriptions. Overall, the present study offers new data and tools that will be instrumental in building a frame of reference for forensic taphonomy in Canada which accounts for its environmental diversity (5 different climates [A, B, C, D, and E] and 29 sub-climates, Dfb being one of them [40]). Future studies will consider donors deposited in winter and will discuss longer term decomposition trajectories at the REST[ES] facility, in keeping with the recent literature that shows an important gap in the knowledge on long PMIs and later stages of human decomposition [13, 38].

5 | CONCLUSION

The scoring system developed in this study offers the first tool to document human decomposition at the REST[ES] facility. A variety of taphonomic patterns were observed, the most noteworthy desiccation, a phenomenon that had been overlooked previously in southern Quebec. As such, the decomposition trajectory at REST[ES] represents a shift compared to what has been considered a 'standard' in forensic taphonomy. This study demonstrates the importance of considering the local climatic conditions when evaluating the extent of decomposition of human remains in not only experimental settings but also in forensic scenarios involving human remains. It provides new data that will be instrumental to establish the first baseline for forensic taphonomy in Quebec to support the Canadian criminal justice system. More generally, the present findings demonstrate the vital importance of conducting further experimental studies on human donors in controlled settings, and in various climatic conditions, to build more comprehensive and reliable taphonomic standards. It is hoped that this study could facilitate comparisons with other locations with comparable climates, including north-eastern USA and northern and eastern Europe, to help build a more accurate picture of human decomposition globally.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

ETHICAL APPROVAL

This research was approved by the Université du Québec à Trois-Rivières Anatomy Laboratory Ethics Sub-committee (*Sous-comité d'éthique du laboratoire d'enseignement et de recherche en anatomie*) (CER-19-261-07.10).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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