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Title: Precocious natural mummification in a temperate climate (Western Cape, South Africa)

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Corresponding Author: Dr. Devin Alexander Finaughty, Ph.D.

Corresponding Author's Institution: University of Cape Town

First Author: Devin Alexander Finaughty, Ph.D.

Order of Authors: Devin Alexander Finaughty, Ph.D.; Alan G Morris, Ph.D.

Abstract: The general process and pattern of decomposition is well-documented and understood. However, specific environmental conditions may alter this pattern and prematurely terminate the decay process. An example of this is natural mummification - a preservative process characterized by desiccation, brittleness and shrinkage of the skin and body tissues. It is important to understand how, when, and where such variations may occur, and for this reason environmentally-specific studies of decay are required. The aim of the present study was to establish baseline data on soft-tissue decomposition in two terrestrial habitats in the Western Cape. A total of 16 pig carcasses serving as analogues for humans were deployed in these habitats during two successive winters and summers between 2014 and 2016. The rate and pattern of decomposition were assessed via measurement of weight loss over time and scoring the decomposition process using Megyesi and colleagues' [1] Total Body Score system and study-specific criteria for mummification. Carcasses typically followed the expected pattern of decay with a few exceptions, most notably instances of rapid natural mummification. Natural mummification, as defined by Megyesi and colleagues [1], was observed to occur as early as 17 days postmortem, with five carcasses mummifying in less than one month. The timing of natural mummification varies widely, from a few days to several years, averaging around three months in temperate regions. Natural mummification occurring in less than one month is termed precocious mummification and is rarely observed in temperate regions. With only three reports globally, this study's findings are globally significant, highlighting the importance of regionally-specific decomposition studies. Two local forensic cases wherein precocious mummification has been observed are also presented and, considered together with the study's results, a possible mechanism driving this process is proposed.

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Finaughty, D.A.¹ & Morris, A.G.¹

¹Department of Human Biology, University of Cape Town, Cape Town, W.C., South Africa.

Corresponding Author:

Dr. Devin Finaughty

Email: devfinaughty@hotmail.com

Tel: +27(0)82-772-1170

Fax: +27(0)21-448-7226

Postal Address: *Department of Human Biology, Anatomy Building, Level 5, Room 5.14.*
Faculty of Health Sciences, University of Cape Town, Anzio Road, Observatory, Cape Town,
Rep. of South Africa (7925)

Author Contact Details:

Dr. Devin Finaughty: devfinaughty@hotmail.com | +27(0)82-772-1170

Prof. Alan Morris: alan.morris@uct.ac.za | +27(0)21-791-0500

ORCID Details:

Dr. Devin Finaughty: <https://orcid.org/0000-0003-2585-1189>

Prof. Alan Morris: N/A

Highlights

- Baseline data establishment for decomposition, temperate southwestern South Africa
- Decomposition in summer frequently results in soft-tissue mummification
- Five carcasses mummified completely in under 30 days – precocious mummification
- Two local forensic cases confirmed to have experienced precocious mummification
- First report of extensive precocious mummification in temperate climate globally

Abstract

The general process and pattern of decomposition is well-documented and understood. However, specific environmental conditions may alter this pattern and prematurely terminate the decay process. An example of this is natural mummification – a preservative process characterized by desiccation, brittleness and shrinkage of the skin and body tissues. It is important to understand how, when, and where such variations may occur, and for this reason environmentally-specific studies of decay are required. The aim of the present study was to establish baseline data on soft-tissue decomposition in two terrestrial habitats in the Western Cape. A total of 16 pig carcasses serving as analogues for humans were deployed in these habitats during two successive winters and summers between 2014 and 2016. The rate and pattern of decomposition were assessed via measurement of weight loss over time and scoring the decomposition process using Megyesi and colleagues' [1] Total Body Score system and study-specific criteria for mummification. Carcasses typically followed the expected pattern of decay with a few exceptions, most notably instances of rapid natural mummification. Natural mummification, as defined by Megyesi and colleagues [1], was observed to occur as early as 17 days postmortem, with five carcasses mummifying in less than one month. The timing of natural mummification varies widely, from a few days to several years, averaging around three months in temperate regions. Natural mummification occurring in less than one month is termed precocious mummification and is rarely observed in temperate regions. With only three reports globally, this study's findings are globally significant, highlighting the importance of regionally-specific decomposition studies. Two local forensic cases wherein precocious mummification has been observed are also presented and, considered together with the study's results, a possible mechanism driving this process is proposed.

Introduction

The general process and pattern of soft-tissue decomposition is well-documented and understood [1,2]. The initial driving force is a result of cellular autolysis, initiated by death, where intracellular nutrients are spilled into the surrounding tissues facilitating the proliferation in now-unregulated internal bacteria population [3,4]. These bacteria begin digestion of internal tissues, a by-product of which is gas. The accumulation of internal gas presents as bloating and purging of fluid and gases from orifices. This release acts as chemical signals attracting various fauna to the carcass, including flies (Order: Diptera), beetles (Order: Coleoptera), and mammalian and avian scavengers [5]. These animals, together with bacterial, enzymatic, and physical action, break down and remove the body's tissues. Putrefaction quickly follows and a rapid decrease in biomass occurs; the end point being skeletonization [6]. This successional pattern of decomposition from fresh to bloat to putrefaction to skeletonisation is often the expected. However, unexpected patterns may occur during this process, mainly because of differences in environment.

Within the study of taphonomy it is accepted that the rate and process of decay is strongly dependent on the environment in which it occurs [7]. Specific environmental conditions may accelerate or slow down decay, or may alter the pattern entirely and bring about preservation [6]. The key to preservation is cessation of the decay process through termination and/or exclusion of the biotic agents of decomposition. This may be achieved naturally or artificially via freezing, anaerobic/bactericidal conditions (e.g. bog/copper salt preservation, saponification), or desiccation. The latter, otherwise known as mummification, is one of the most common forms of preservation. Mummified remains are characterised by desiccated, brittle skin shrunken over bony prominences. The skin is often adherent to the underlying bone – its creases and folds tough and fixed – and the body's internal tissues presenting differentially as wholly or partially

mummified, putrefied, entirely absent, or with adipocere (“grave wax”), depending on the time since death [8-10].

Preservation is favorable for identification purposes but is usually the exception rather than the norm. Preservative processes require specific environmental conditions, the combination and magnitude of which influence the degree and timing of preservation. Spontaneous natural mummification, specifically, is generally associated with arid conditions (hot or cold) such as may be found in the southwestern regions of North America and southwestern Africa, the dry coastal plains of South America, the deserts of North Africa, the Middle East and Australia, the polar regions in far north Asia, North America and Antarctica, and high altitude locales on every continent [11,12]. Outside of these regions, spontaneous natural mummification is not a common occurrence. Although it is not unheard of in temperate climates, it is not a frequently reported occurrence [9,13]. This is particularly noteworthy given that it stands in stark contrast to the reality experienced in the City of Cape Town, located in the Western Cape province of South Africa.

A biogeographically unique region at the southern tip of Africa, the Western Cape is the only African temperate Mediterranean climate south of the Sahara, replete with distinctive geography and thousands of faunal and floral species found nowhere else on Earth. Socially, and of forensic significance, the City of Cape Town Metropole, South Africa’s second largest city, has the highest murder rate in Africa – 62/100,000 people. Ten of the top 30 police stations for murder in South Africa are located within the city [14]. Over 14% of the nearly 27,000 victims of unnatural death which have passed through the city’s mortuaries in the last seven years have been in a state of decomposition or skeletonisation (n = 345), oft displaying signs of mummification to varying degrees, inclusive of complete mummification [15]. Understanding this in the context of the forensic death investigation, particularly for the purposes of estimating the postmortem interval, has proven nearly impossible for two reasons: firstly, no regional data existed on the rates and processes of decomposition. In such circumstances one may turn to the literature for guidance, but a second problem was encountered: the timing of spontaneous natural mummification is not well documented [9]. This is mainly due to the gradual nature of the onset and progression of spontaneous natural mummification and the long periods of time that elapse before the discovery of a body: the circumstance wherein mummification is most frequently encountered in the forensic setting [8]. Case reports in the literature describe a wide range: from as little as two weeks postmortem [16] to more than 12 months [10], but most authors agree that it takes an average of several weeks to months [9,10,13,17]. In temperate climates, the figure is stated to be at least three months [18]. Spontaneous natural mummification in four weeks or less is considered to be rapid and is referred to as precocious mummification [10].

Given the deficit of appropriate knowledge for accurate estimation of the postmortem interval in the local circumstance, particularly where mummified remains are concerned, a study was undertaken to establish baseline data on soft-tissue decomposition in Cape Town (as a starting point for the wider Western Cape). A part of this study was dedicated to examining the timing and possible mechanism(s) of spontaneous natural mummification in the local circumstance. These are presented and discussed below alongside two relevant forensic case reports.

Materials and Methods

Study location

The research was conducted in two locally forensically significant habitats of the City of Cape Town Metropole, Western Cape province, South Africa (Figures 1a, b). The region is characterized by a temperate climate with winter rainfall and warm, dry summers (Köppen-Geiger climate classification: Csb) [12] (Figure 1c). The habitats in question are the indigenous Cape Flats Dune Strandveld (CFDS) – a flat to slightly undulating landscape with sandy, nutrient-poor soils and low, scrub-like vegetation (Figure 1d) – and portions of the CFDS invaded by the invasive trees Port Jackson (*Acacia saligna*) and Rooikrans (*Acacia cyclops*) which form dense thickets (Figure 1e). Both habitats fall within the most densely populated regions of Cape Town (>3,000 people/km²) which also have the highest murder rates. Twenty of the city’s policing districts are in the top 20% in terms of number of murders nationally [14], hence the local forensic significance. The habitats were designated as open CFDS (CFDS/O) and thicketed (closed) CFDS (CFDS/C).

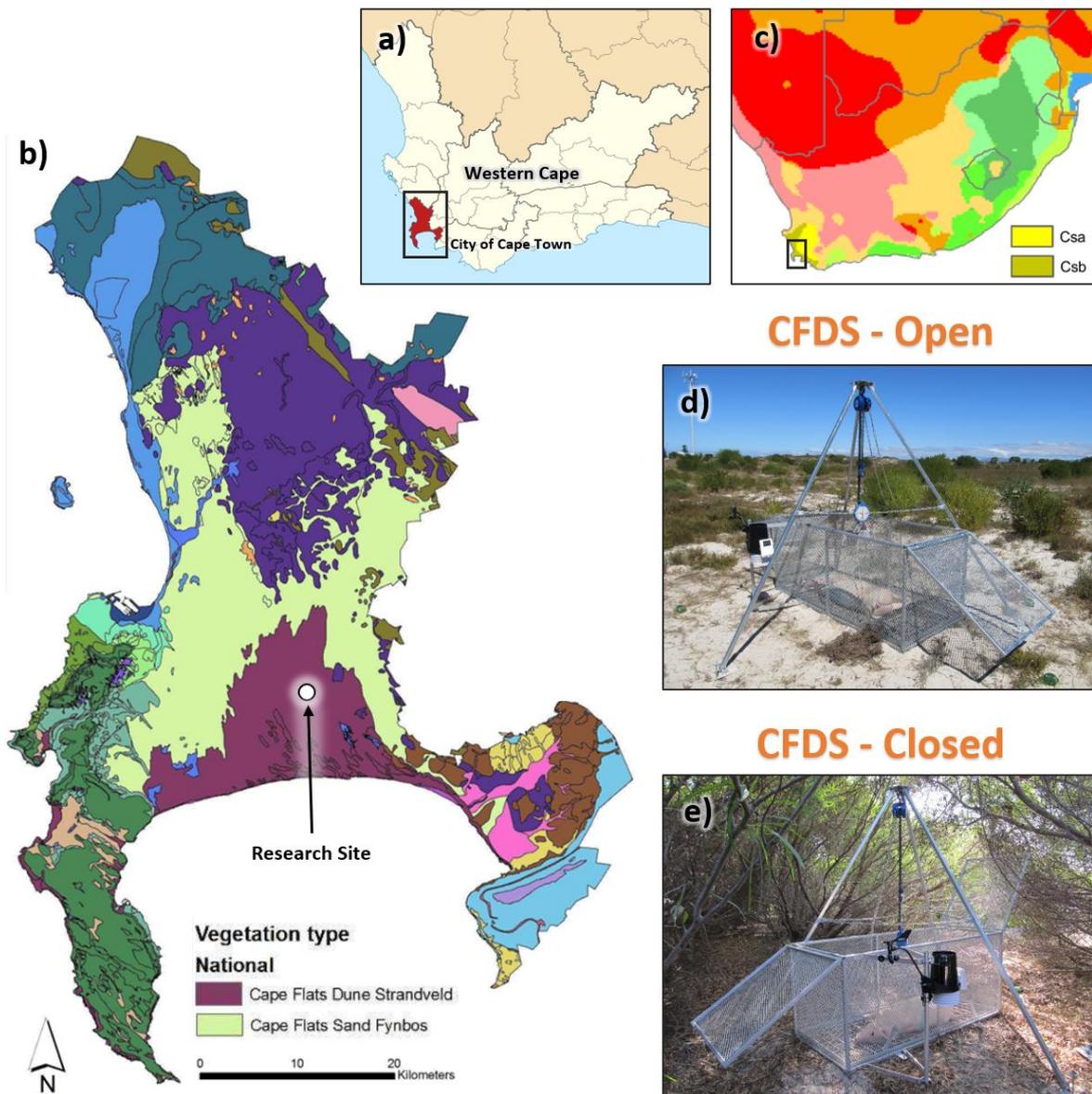


Figure 1. Maps of the City of Cape Town Metropole indicating: (a) the municipality’s position within the Western Cape province of South Africa (adapted from [19]); (b) the vegetation sub-types within the municipal borders with relevant sub-types keyed and Cape Flats region

highlighted (adapted from [20]); (c) the Köppen-Geiger climate type map of South Africa [12]; (d-e) the open and closed CFDS habitats showing the experimental setup. This composite figure is adapted from [21].

Data collection – decompositional study parameters

Data were collected over four seasonal trials (two replicates each of summer and winter), starting in July 2014 and ending in March 2016. Winter trials ran from the early July to late November, and summer trials from early January to the end of March. The experiment employed freshly-killed domestic pig (*Sus scrofa* L.) carcasses, controlled as far as possible for sex, mass, subcutaneous fat depth, size, and manner of death [22]. Domestic pigs are generally acceptable analogues for human cadavers where the establishment of baseline data is concerned, and human bodies are not available for the purpose [23-26]. Carcasses were humanely euthanized via ear-to-ear stunning and a single .22LR gunshot to the base of the brain. Ethical approval for this procedure was granted by the University of Cape Town Animal Ethics Committee in March 2014 (UCT FHSAEC Ref. 014/004). Following euthanasia they were washed, placed into body bags, and immediately transported to the research site.

For each seasonal trial, two carcasses were deployed in each of the two habitats under study, for a total of 16 carcasses. Equal numbers of males and females were used for each trial to ward against sex-specific sampling bias. Carcasses were placed in standardized positions on a steel weighing grid within a specially-designed and purpose-built steel cage (Figures 1d, e), with each cage a minimum distance of 30 m to prevent overlap of attendant crawling insect populations at each carcass [27]. Caging was elected to protect the carcasses against theft whilst still fresh, and from removal/dispersal by large scavengers, e.g. [28-31]. Although this narrows the scope of forensic applicability of the results, it is still appropriate for the aim and objectives of the study considering in only 11% of the forensic investigations undertaken by the local service provider in Cape Town (Forensic Anthropology Cape Town [FACT]) in the last 10 years have the remains presented with signs of scavenging. Accordingly, the results could still be applicable to the majority of local forensic cases.

Data were gathered on the prevailing weather conditions, the state of decay, the insect populations inhabiting the remains, and scavenging by small mammals (when applicable). Weather data were collected quarter-hourly via a Davis Vantage Pro 2 weather station (Davis Instruments, Hayward, California) in each habitat. Variables measured included ambient temperature (°C), ambient relative humidity (%), wind speed (km.h⁻¹) and direction, rainfall (mm), and solar radiation intensity (W.m⁻²).

Data collection – assessing decomposition and mummification

The rate and process of decomposition was catalogued via tracking daily weight loss and scoring decomposition using Megyesi and colleagues' [1] Total Body Score (TBS) system. For the latter, the physical appearance of each carcass was scored daily per Megyesi and colleagues' [1] unaltered criteria to generate a daily carcass-specific TBS (Table 1). The method assigns scores to qualitative decompositional characteristics in three regions of the body: the head/neck, thorax/abdomen, and limbs. This is due to the fact that decomposition may proceed at different rates in these regions, and not all regions of the body present with precisely the same patterns of decay [32]. These scores are then combined to produce the TBS. The TBS may range from a

minimum of 3 (representing a fresh body), to a maximum of 35 (representing dry bone in all three regions). The TBS corresponds to a specific stage of decomposition, meaning progression of a carcass' TBS corresponds to progression of its decomposition through the four decomposition stages defined by Megyesi and colleagues [1]. The criteria recognize mummification, placing it at the end of advanced decomposition with a TBS ranging from 22 (only one region mummified) to 24 (whole body mummified). In addition to scoring TBS, the day on which any region of tissue representing 1% or more of a carcass first mummified was noted. Criteria for establishing mummification included determining if the region under assessment presented with desiccated, brittle skin in a fixed position (i.e. lacking compliance) and shrunken over and/or adherent to underlying bony prominences, where applicable. This was done to delineate the point at which mummification began, which Megyesi and colleagues' [1] method does not do as it only establishes the onset of mummification once an entire region of the body (i.e. the whole head/neck, or entire thorax/abdomen, or all four limbs – each in their entirety) has become mummified. Completion of mummification was defined as all three regions of the carcass attaining a state of mummification as defined by Megyesi and colleagues' [1] criteria (i.e. TBS = 24).

To help correlate faunal activity with the onset and progression of mummification, the populations of local forensically significant insect species were monitored via daily observation and sampling. Information was collected on the species assemblage and life stage(s) present for each species. Blow fly larval masses were monitored for visible size and extent of dispersion on each carcass. Incidental scavenging by small mammals (principally Cape grey mongoose [*Galerella pulverulenta*]), largely localized to the CFDS/C habitat, was tracked via motion-activated infrared trail camera ('camera trap') photography) in the second winter and summer seasonal cycle.

Statistical analyses

Hypothesis testing was then performed on the time (in 24hr days) and heat energy (in Accumulated Degree Days) associated with the onset and completion of mummification using a Kruskal-Wallis test for non-parametric data. The null hypothesis stipulated no differences in the means/medians (where applicable) of each measure between seasons and habitats; the alternative hypothesis stipulated significant differences in the means/medians (where applicable) of each measure between seasons and habitats. A p -value of ≤ 0.05 was chosen as the cut-off for significance. Paired sample t-tests were used to determine if the actual ADD values associated with the onset and completion of mummification per Megyesi and colleagues' [1] definitions differed from the ADD values predicted with Megyesi and colleagues' [1] formula ($ADD = 10^{(0.02 * TBS * TBS + 1.81)} \pm 388.16$).

Results

Weather

Cape Town's Mediterranean climate was well-reflected in the data, with some interesting and relevant observations in summer seasonal cycles. Specifically, the 24hr maximum temperature exceeded the average maximum temperature for the hottest month in Cape Town (32°C; February) on 10% of the days in the first summer cycle, and more than double that during the second summer cycle. Of these, 40% in the first summer cycle and almost 50% in the second

summer cycle saw the modal day time temperature within 1°C of the maximum. In short, these were hot days, and they did not occur in isolation. Two instances, both in the second summer, occurred wherein these conditions persisted for more than three consecutive days (a “hot spell”). The longest of these was eight consecutive days. In most instances, in both summer cycles, hot days were preceded or succeeded by at least one day wherein the maximum ambient temperature was still around 30°C. These thermal conditions were often associated with high solar radiation ($> 600 \text{ W.m}^{-2}$), low daytime humidity ($< 50\%$), and/or windy conditions (sustained speeds and/or gusts exceeding 30 km.h^{-1}) either on the same day or within two days on either side. Taken together, each season presented with a series of multi-day clusters of these drought-like conditions: six in the first cycle, and five in the second cycle (Figures 2, 3).

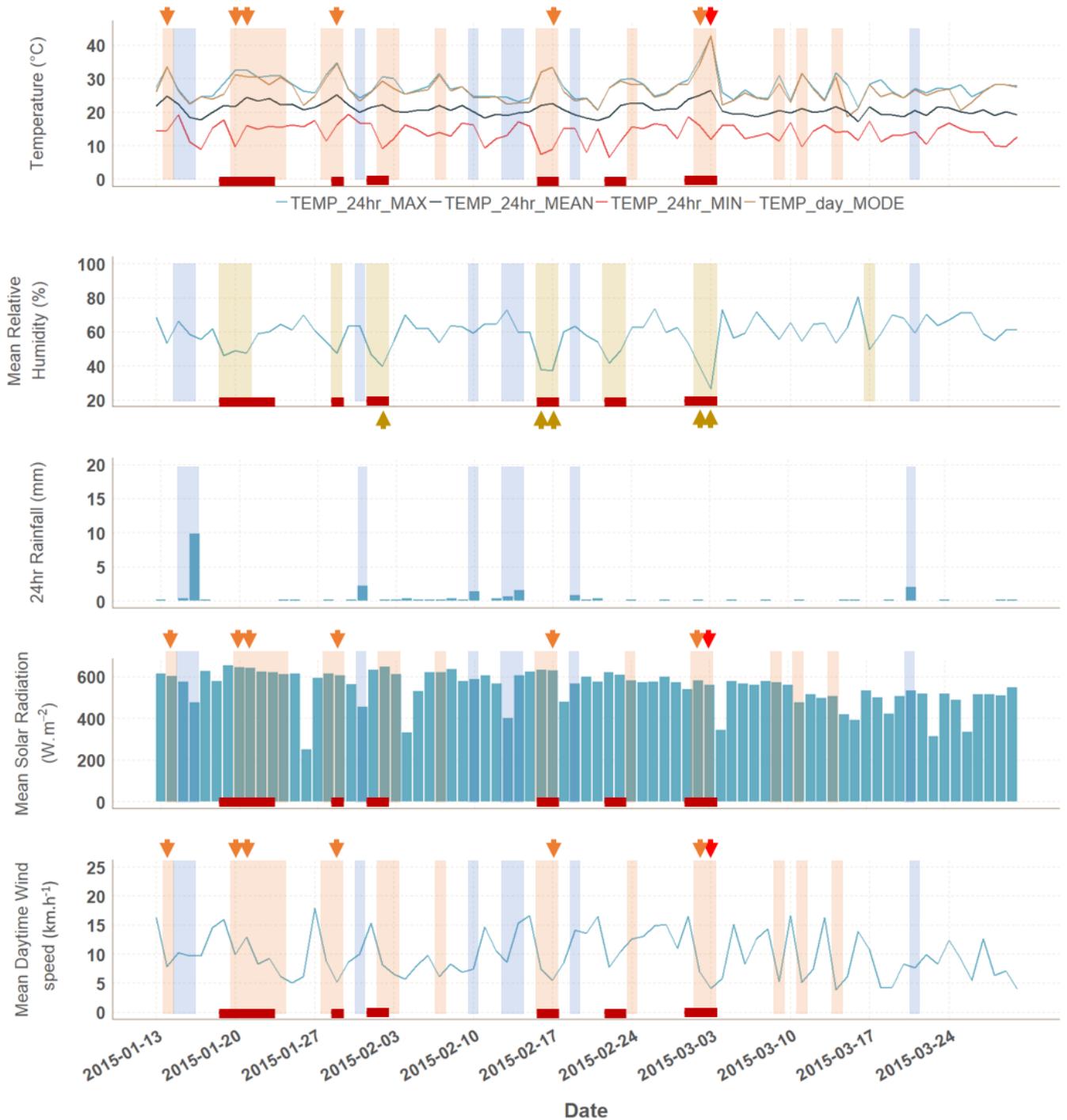


Figure 2. Temperature (ambient; 24hr maximum, minimum and mean, daytime modal), relative humidity (%), 24hr rainfall (mm), mean solar radiation ($\text{W}\cdot\text{m}^{-2}$), and mean daytime wind speed data ($\text{km}\cdot\text{h}^{-1}$) for Cycle 2 (S-2015). Seven hot days are indicated with \downarrow , one heat spike is indicated with \downarrow , six cold fronts are highlighted with \square , 19 days with a maximum ambient temperature $> 30^\circ\text{C}$ are highlighted with \square , five dry days are indicated with \uparrow , 13 days with mean daytime humidity $< 50\%$ are highlighted with \square ; six spells with drought-like conditions are indicated with \blacksquare (the length of which indicates duration).

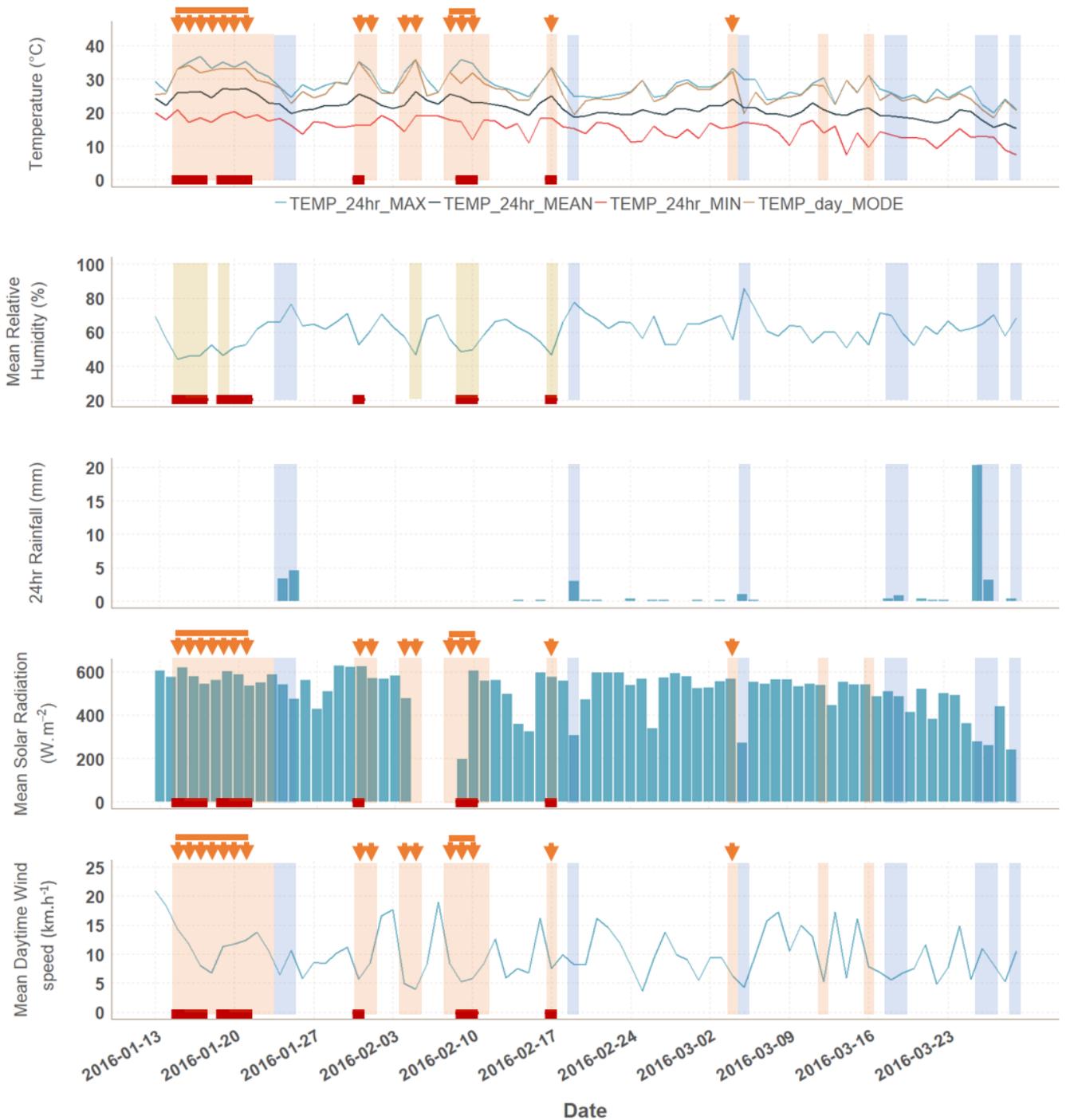


Figure 3. Temperature (ambient; 24hr maximum, minimum and mean, daytime modal), relative humidity (%), 24hr rainfall (mm), mean solar radiation ($\text{W}\cdot\text{m}^{-2}$), and mean daytime wind speed data ($\text{km}\cdot\text{h}^{-1}$) for Cycle 4 (S-2016). 16 hot days are indicated with \blacktriangledown , two hot spells are denoted by \blacksquare (the length of which indicates duration), six cold fronts are highlighted with \blacksquare , 21 days with a maximum ambient temperature $> 30^\circ\text{C}$ are highlighted with \square , eight days with mean daytime humidity $< 50\%$ are highlighted with \square ; five spells with drought-like conditions are indicated with \blacksquare (the length of which indicates duration).

Decomposition

Carcasses largely followed the expected pattern of decay as outlined in the introduction, with one important distinction: almost all experienced a period of stasis wherein the remains were preserved. The only preservation state observed during the experimental period was spontaneous natural mummification via desiccation of soft tissues. This preservation state was observed to occur in both habitats and in both seasons. Mummification was most frequently observed to begin in the head region, although there were some instances wherein it began on the limbs.

The results of the timing of mummification are presented in Tables 1 and 2. Using Megyesi and colleagues' [1] definitions, the onset of mummification (i.e. when any one region of the carcass assumed a state of mummification) occurred as early as 17 days in summer (ADD397.84), and 73 days in winter (ADD972.43). Using this study's definitions, the earliest onset of mummification (i.e. where any portion of the body comprising $\geq 1\%$ of total body surface area mummified) occurred within 8 days in summer (ADD230.78), and 49 days in winter (ADD622.75). Completion of mummification occurred as early as 17 days in summer (ADD397.84), and within at least 77 days in winter (ADD1035.18). Most interestingly, five of the 16 carcasses studied were completely mummified within one month (30 days) postmortem (ADD664.84-736.64), all during summer cycles (two in Cycle 2 | S-2015, and three in Cycle 4 | S-2016). Three of these were from the CFDS/O habitat; the other two were from the CFDS/C habitat. Illustrations of what these carcasses looked like at the onset (own study definitions) and completion of mummification are available in Figure 1 of the supplementary material. Seasonal differences in the timing (in 24hr days) of these milestones are significant, but between habitats they are not. That said, the onset of mummification occurs sooner, on average, in the CFDS/O, but reaches a state of completion sooner, on average, in the CFDS/C.

The amount of heat energy associated with the onset and completion of mummification is presented in Tables 3 and 4. In general, less heat energy is associated with these milestones in summer compared to winter, but this is only significant for the completion of mummification (Table 3). The onset of mummification occurs sooner in the CFDS/O than in the CFDS/C, significantly so when using Megyesi and colleagues' [1] definitions. Little difference exists between habitats with respect to the amount of heat energy associated with the completion of mummification (Table 4).

Table 1: Time (in 24-hour days) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing season.

		Summer (n=8)	Winter (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median	20.50	92.00	49.50	11.344	*0.001
	(IQR)	(3.00)	(25.00)	(72.00)		
	(Range)	(17-26)	(73-112)	(17-112)		

Onset of mummification (this study)	Median (IQR) (Range)	12.50 (11.00) (8-20)	65.50 (14.00) (49-75)	34.50 (55.00) (8-75)	11.344	*0.001
Completion of mummification (Megyesi)	Median (IQR) (Range)	28.50 (23.00) (17-67)	109.50 (19.00) (77-124)	72.00 (84.00) (17-124)	11.311	*0.001

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

Table 2: Time (in 24-hour days) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing habitat.

		CFDS/O (n=8)	CFDS/C (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median (IQR) (Range)	52.00 (71.00) (17-112)	49.50 (79.00) (20-112)	49.50 (72.00) (17-112)	0.335	0.563
Onset of mummification (this study)	Median (IQR) (Range)	31.50 (54.00) (8-68)	41.00 (50.00) (8-75)	34.50 (55.00) (8-75)	0.543	0.461
Completion of mummification (Megyesi)	Median (IQR) (Range)	70.88 (83.00) (17-124)	68.13 (83.00) (23-115)	72.00 (84.00) (17-124)	0.003	0.958

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis; **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

Table 3: Accumulated Degree Days (ADD) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing season.

		Summer (n=8)	Winter (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median (IQR) Range	564.27 (126.24) 397.84-703.69	1179.96 (787.17) 214.86-1410.94	791.24 (712.60) 214.86-1625.80	2.824	0.093
Onset of mummification (this study)	Median (IQR) Range	295.07 (203.02) 230.78-458.58	725.89 (579.59) 139.13-1003.78	422.09 (527.60) 139.13-1003.78	2.828	0.093
Completion of mummification (Megyesi)	Median (IQR) Range	677.44 (449.88) 397.84-1425.28	1536.48 (391.10) 1035.18-1800.43	1188.61 (916.38) 397.84-1800.43	8.647	*0.003

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

Table 4: Accumulated Degree Days (ADD) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing habitat.

		CFDS/O (n=8)	CFDS/C (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median (IQR) Range	545.79 (516.52) 214.86-1297.40	972.43 (731.12) 523.75-1625.80	623.81 (712.60) 214.86-1625.80	2.692	*0.007
Onset of mummification (this study)	Median (IQR)	256.38 (271.72)	803.94 (418.88)	422.09 (527.60)	7.296	0.101

(this study)	Range	139.13-647.83	385.59-1003.78	139.13-1003.78		
Completion of mummification (Megyesi)	Median	1271.15	1106.07	1188.61	0.339	0.560
	(IQR)	(914.72)	(813.17)	(916.38)		
	Range	397.84-1800.43	603.88-1689.39	397.84-1800.43		

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

The results of an assessment of the accuracy of Megyesi and colleagues' [1] scoring system with respect to mummification in the local habitat are presented in Figure 4 below. The system predicts the ADD values associated with the onset of mummification (TBS22) well in summer and in the CFDS/O habitat. The accuracy declines in winter and in the CFDS/C habitat, with the predicted value for winter significantly underestimated (Figure 4a). The ADD value for TBS values denoting completion of mummification (TBS24) was less well-predicted, generally being underestimated in both habitats and in winter. Interestingly, it was overestimated in summer, with only two exceptions which were higher than predicted. None of these differences were, however, significant.

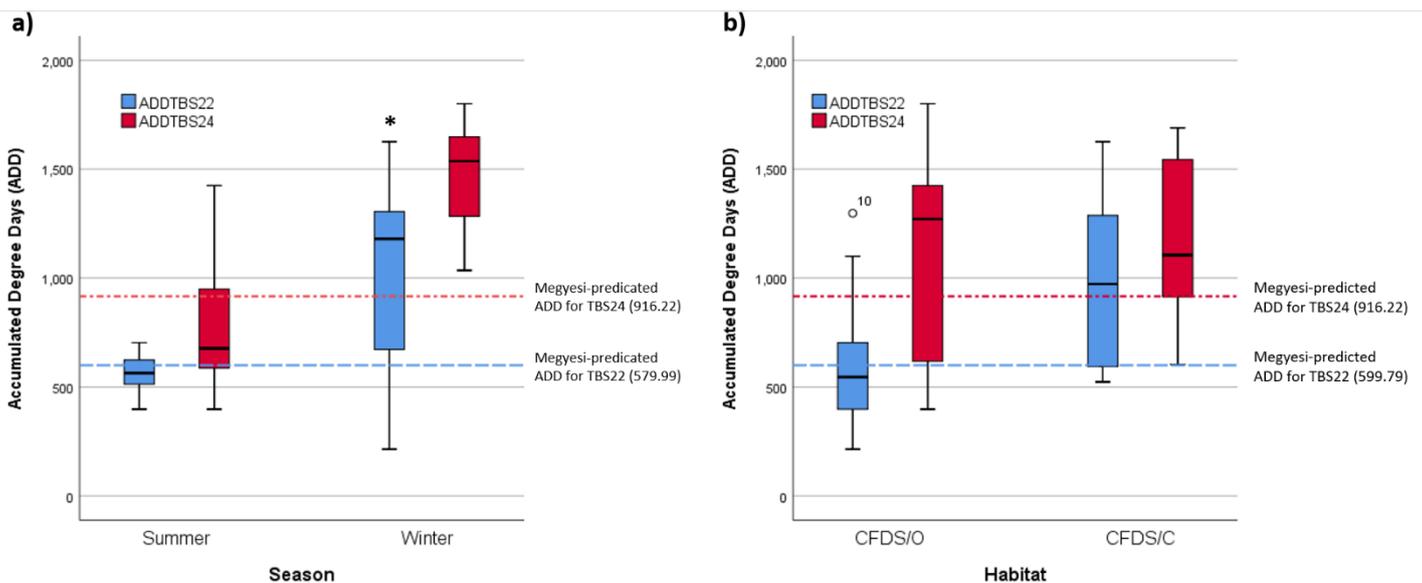


Figure 4. Boxplots showing the spread of actual ADD values associated with TBS values 22 (onset of mummification) and 24 (completion of mummification), benchmarked against ADD values predicted by Megyesi and colleagues' [1] formula: 599.79 for TBS22 and 916.22 for TBS24. A seasonal comparison is shown in (a) where the predicted ADD for TBS22 was significantly underestimated ($M=419.77$, $SD=487.58$); $t(7)=2.435$, $p = 0.045$. A habitat comparison is shown in (b) where the predicted ADD is generally underestimated in both habitats, with the exception of the ADD associated with TBS22 in the CFDS/O where actual ADD values cluster closely around the predicted ADD.

Discussion

Micozzi [11] viewed the decay process as a “competition between decomposition and desiccation”. He highlighted the interplay of the variables of the decomposition ecosystem as the determinant of the outcome of this contest. Ergo, a combination of variables which favor desiccation over putrefaction is more likely to result in preservation of the remains. It is well-known that hot, dry environments favor desiccative preservation, although desiccation may occur at any temperature; the prerequisite is a lack of environmental moisture [8,9,11,33]. Numerous regions of the world characterise these conditions, but temperate climates are not generally cited among them. This makes the observations of multiple instances of spontaneous mummification via natural desiccation in the present study a particularly interesting finding. The fact that five of these could be defined as precocious (i.e. having occurred in less than 30 days) is even more interesting given that reports of precocious mummification are few and far between, and generally associated with climatic extremes. Examples include: Kashimura and colleagues’ [34] report of a body mummified within 25 days inside a prefabricated structure in Japan during a heatwave; Galloway and colleagues’ [35] report of the mummification of bodies in as little as 11 days in the arid climate of Arizona, USA; and similar timeframes reported by Rhine and Dawson [16] in the arid New Mexico, USA climate. Only one report of confirmed precocious mummification in a temperate climate exists: Marella and colleagues [10] reported a case from Italy wherein mummification of human remains occurred within four weeks of the disappearance of the individual.

The rarity of the occurrence of precocious mummification relates to the specificity of the conditions which facilitate it (i.e. prolonged hot, dry and/or windy conditions – drought-like). Megyesi and colleagues [1] even altered their TBS scoring criteria to take this fact into account. Spontaneous natural mummification is only reported in temperate climates wherein other factors have contributed to its onset. The report by Marella and colleagues [10], for example, cite the fundamental role of the massive perimortem trauma experienced by the deceased. The individual had been hit by a train, resulting in body-wide lacerations and amputations which allowed significant exsanguination and subsequent dehydration of the tissues. The reports by Kashimura and colleagues [34] and Campobasso and colleagues [9] illustrate how a warm, dry microclimate – such as that which may occur in a closed room or house – can result in spontaneous natural mummification, including in a temperate climate. However, no such contributory factors are at play in the present study. All five carcasses which experienced precocious mummification were largely comparable in biographics and intact, with only a small bullet wound to the top of the head which sealed with clots in the immediate aftermath of death, and all were exposed to similar environmental conditions. These observations thus represent the first report of spontaneous precocious natural mummification without major contributory factors in any temperate region in the world.

This, then, begs the question: if there are no confounding/contributory factors such as those reported in the literature where precocious mummification is observed, what is driving the process in the Western Cape? It is argued that much of the answer lies in the unique summer weather of Cape Town which sees spells of drought-like conditions (see Figure 5 for schematic of proposed mechanism). As noted in the weather results, these spells are characterised by two or more consecutive days presenting with a specific combination of weather criteria known to promote mummification (i.e. hot, dry, and windy). Thus, this would include a 24-hour maximum ambient temperature greater than 30°C (i.e. hot), a mean solar radiation load greater than 600 W.m⁻² (i.e. hot), a mean daytime ambient humidity less than 50% (i.e. dry), and daytime windspeed/gust measures in excess of 30 km.h⁻¹ (i.e. windy). Days with these conditions may be preceded or succeeded by days with some, but not all, of these four criteria, although they would

still likely contribute to the promotion of mummification. Looking at the timing of these spells, they fall within the first three weeks of decay in both summer cycles, when the carcasses are in early decomposition and bacterial and blow fly larval activity is highest. It is known that blow fly larval and bacteria masses generate their own heat, with temperatures close to 30°C over and above the ambient temperature reported [6,36,37]. This means that, during these spells, the temperatures blow fly larvae are exposed to has the potential to well-exceed 50°C – above the lethal thermal threshold of all the forensically significant blow fly species noted on the carcasses in summer seasonal cycles (*Lucilia* spp. = 47.8°C, *Chrysomya albiceps* = 48.8°C, *Chrysomya marginalis* = 50.1°C [39]). This would result in mass mortality of blow fly larvae, swiftly removing one of the principle external drivers of decay, such as that observed by Kelly and colleagues [39]. Such conditions are not short-lived, though, and persist for as long as five days. Anecdotally, it was noted that blow fly activity was considerably reduced on days with drought-like conditions, meaning that potential blow fly oviposition would also be reduced. Under such conditions, any existing blow fly eggs may also enter a state of diapause and delay hatching until conditions are more favorable [6]. At the same time, exposed tissues of the carcasses would desiccate, inhibiting the carcass putrefactive activity of bacteria and fungi which require water to function and proliferate [33]. It is also known from the literature that gravid female blow flies will not oviposit on desiccated tissues due to the high susceptibility of eggs and young larvae to desiccation [6,40-42]. This means that once favorable conditions for blow fly eggs and larvae resume the proportion of the resource available to them is reduced, which may negatively affect their survivability. Similarly, less of the carcass is available for new oviposition. Taken together, new larval masses will be smaller and therefore less tissue may be consumed than may otherwise have been prior to the onset of mummification-inducing conditions. The reduction in consumption of tissues by insects serves to reduce the rate at which the body's cavities are opened up, limiting the resurgence of aerobic bacterial populations and retarding this aspect of bacterial-driven decay [43].

Cumulatively, the above represents functional exclusion of the bacteria- and insect-mediated decomposition of the carcasses during each one of these hot, dry and windy spells – a core prerequisite for the promotion of mummification. It is, thus, proposed, that such conditions be formally defined as **mummification-inducing**, with the following criteria: a 24hr maximum temperature > 30°C, a mean solar radiation > 600 W.m⁻², a mean daytime humidity < 50%, and a windy day (daytime windspeed/gust measures of 20-30 mi.h⁻¹ (32.19-48.28 km.h⁻¹) [44], i.e. “Fresh Breeze” or greater on Beaufort Scale [45]. Days wherein at least three of the four mummification-inducing criteria, or two of the thermal, humidity, and solar radiation criteria, plus at least two consecutive windy days immediately preceding the day in question, may be defined as **near-mummification-inducing**.

Given the above, it is not hard to see how repeated spells of mummification-inducing conditions can strongly retard and even stop bacteria- and insect-mediated decomposition, which, together with environmentally-mediated soft-tissue desiccation, can contribute towards spontaneous precocious natural mummification.

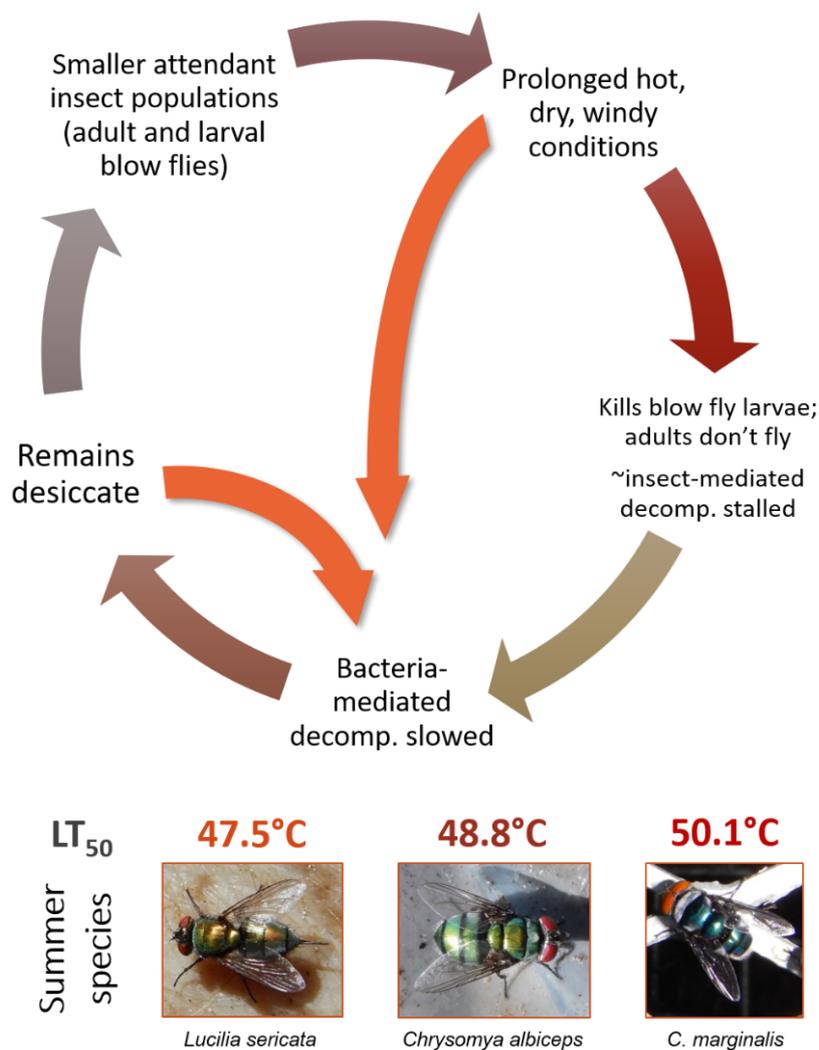


Figure 5. Proposed mechanism driving precocious natural mummification in the Western Cape: (1) prolonged hot spell with dry and windy conditions occurs during early decomposition; (2) blow fly larvae, in masses where temperatures may be > 30°C above ambient, are exposed to temperatures exceeding their lethal thresholds (species-specific), resulting in mass mortality. Blow fly adult activity and bacterial decomposition activity is simultaneously reduced; (3) combination of hot, dry, and windy conditions & reduced/terminated bacteria- and insect-driven decay desiccates remains; (4) bacteria negatively influenced by reduced fluid availability & adult female blow flies will not oviposit on desiccated tissue → less of the carcass is available as a resource → smaller blow fly larval masses post-hot spell; (5) another hot spell arrives and the

cycle repeats; successive hot spells functionally exclude bacteria- and insect-mediated decomposition and simultaneously desiccate the remains. Scavenging by vertebrates may accelerate this process.

Instances of spontaneous precocious natural mummification in the Cape Town region are not restricted to porcine carcasses or the experimental circumstances. With permission of the respective pathologists, we can report that two forensic cases within the last four years have definitively presented with spontaneous precocious natural mummification. The first, which was analyzed prior to attainment of the first summer results of this study, is the strongest evidence of precocious mummification in region. The remains were recovered from exposed circumstances outside Stellenbosch, to the east of Cape Town in February 2015, and, as evident in Figure 6a, presented with classic signs of mummification, and no evidence of perimortem trauma which may have accelerated the mummification process such as that reported by Marella and colleagues [10]. The remains had been scavenged by canids, but this was confined to the forearms and lower legs. At the time of analysis, and lacking local data, it was assumed that the deceased has perished around three months previously – in line with the timeline reported in the international literature for temperate climates (most recently cited in [18]). However, the individual was subsequently identified and had been missing only 10 days at the time of analysis. A second case, from Clanwilliam, two hours north of Cape Town but still within the same biogeoclimatic region (fynbos biome; Csb climate zone), was recovered in October 2017. This individual was similarly



Figure 6. Local forensic cases from (a) Paarl (February 2015) – mummified in 10 days, and (b-c) Clanwilliam (December 2017) – mummified in 3 weeks.

It is prudent to point out that the definition of precocious natural mummification is linked to the passage of a particular period of time (24-hour days). The problem of using this as a comparative measure across different decomposition circumstances has long been recognized and is, indeed, what stimulated Megyesi and colleagues [1] to develop their TBS/ADD scoring system. It would, therefore, be remiss to not include an analysis of how well Megyesi and colleagues' [1] system predicts the occurrence of precocious natural mummification in the local environment. The results are interesting and support those of a previous study assessing the accuracy of Megyesi and colleagues' [1] system at other TBS values for decomposition in the same environment [46]. Specifically, the ADD associated with the onset of mummification is well-predicted in summer and in the CFDS/O where the remains are more exposed to the prevailing weather conditions. However, the ADD associated with the completion of mummification (and, by extension, the attainment of a state of precocious natural mummification) is overestimated, although not significantly so. The system is wholly inaccurate in winter for both mummification milestones, the system consistently underestimating the ADD associated with the milestones. Nor is it as accurate in the CFDS/C, where it is similarly underestimating the ADD. Overall, the results of this study indicate that Megyesi and colleagues' (2005) system does not accurately predict the ADD associated with the occurrence of precious natural mummification in the local habitat and could, therefore, benefit from the inclusion of local data in the model to improve its accuracy for local forensic use. This said, the model's relatively accurate prediction of the ADD associated with the onset of mummification in summer suggests that the criteria for establishing precocious natural mummification could be defined with respect to ADD with the inclusion of more data from confirmed precociously mummified cases (where the 30-day definition was used) – a potentially globally-useful forensic tool.

The results of this study provide some insight into the possible mechanisms driving such rapid mummification. Specifically, the porcine carcasses which experienced precocious natural mummification did so within similar timeframes to these cases, under similar surface exposure circumstances, lacking significant perimortem trauma, and, in the case of two carcasses, with a degree of scavenging of the remains. The observations from these forensic cases are not dissimilar with those from precociously mummified carcasses in this study, suggesting the proposed mechanism of precocious natural mummification may be at work here. Further research directed at quantifying this process may aid in the prediction of PMI in these types of cases – an especially helpful outcome in situations where the deceased cannot be readily identified.

Conclusion

The instances of spontaneous precocious natural mummification observed in this study, supported by two confirmed occurrences from local forensic casework, represent the first reports of this

type of preservation in the absence of contributory factors from any temperate region in the world. Far from being isolated incidences, the wide temporal distribution of these occurrences in a variety of habitats with multiple types of carrion suggests this is a recurrent manifestation in the Cape region. It is argued that this phenomenon is driven, in part, by the region's unique biogeographic circumstances. It is clear that the generally-accepted timeline for spontaneous natural mummification in a temperate climate requires reconsideration. The experience of the authors with the first of the reported forensic cases should serve as a cautionary tale to other forensic practitioners reliant on decompositional data obtained from different biogeographic circumstances to their own. Taken together, these highlight the importance of establishing data for regionally-specific decompositional ecosystems. Understanding the nuances of the decay sequence in varied environments is critical for forensic practice, especially where the estimation of the postmortem interval is concerned. The results pertaining to the use of Megyesi and colleagues' [1] system suggest there is promise for a move from defining precocious natural mummification with respect to time to defining it with respect to the more-comparable ADD. Again, though, this will require the inclusion of more data from confirmed precociously mummified cases where weather data are available. Moving forward from the present study, further research must be undertaken to quantify and validate the mechanism proposed to be at play in bringing about the observed preservation. Tracing the extent of this phenomenon's occurrence in other temperate regions is also important. The authors encourage researchers and forensic practitioners to report confirmed instances of spontaneous precocious natural mummification and provide weather data if available. To quote Piombino-Mascalì, Gill-Frerking, and Beckett [18]: "Natural, or spontaneous, preservation is of tremendous scientific importance." Knowledge on the varied processes driving this phenomenon is crucial for our global understanding of the taphonomy of remains recovered not only from forensic contexts, but from historic and archaeological contexts, too, considering these comprise the majority in which mummies are found.

Conflict of Interest: The authors declare that they have no conflict of interest.

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Figure 1

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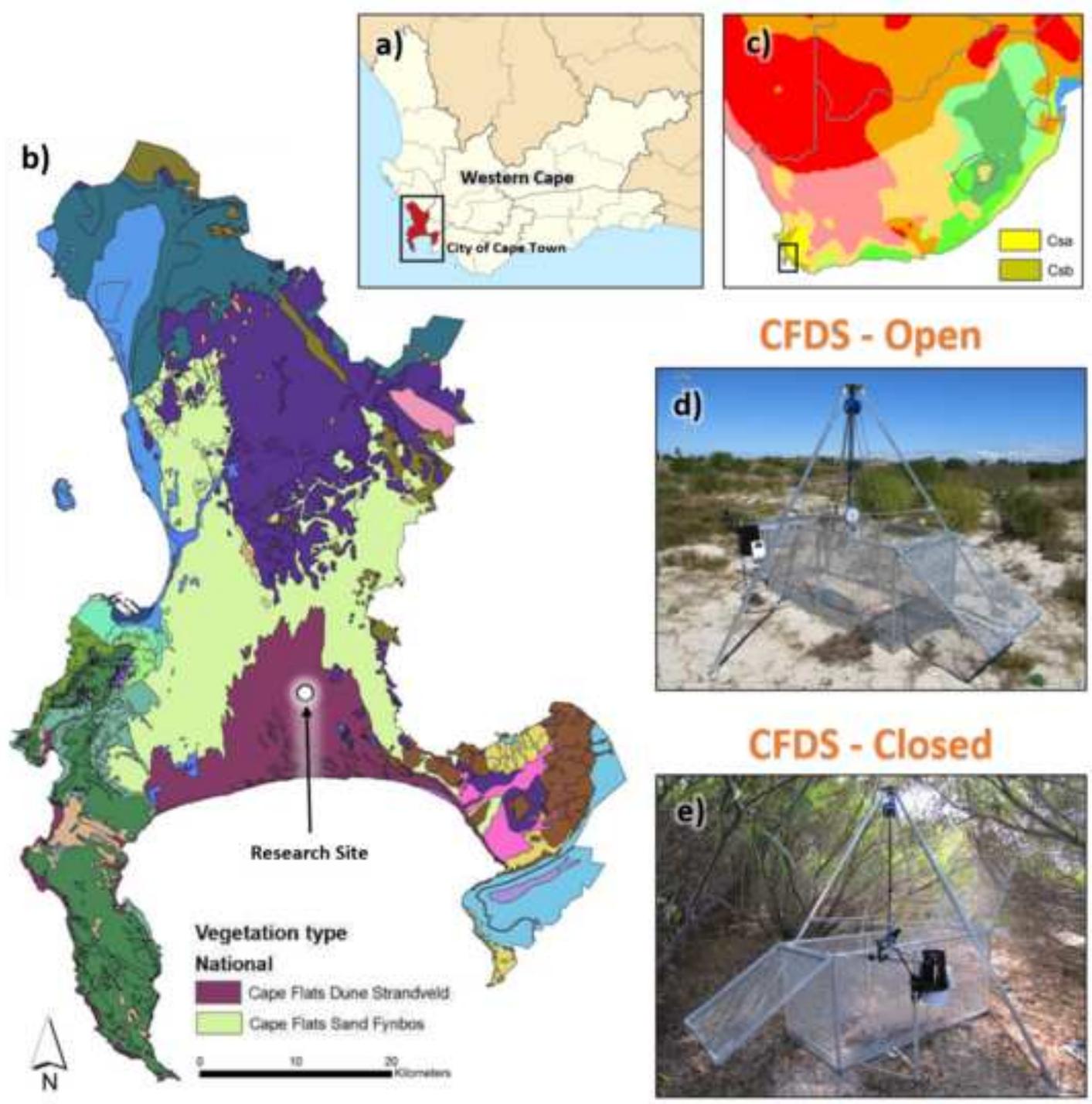


Figure 2

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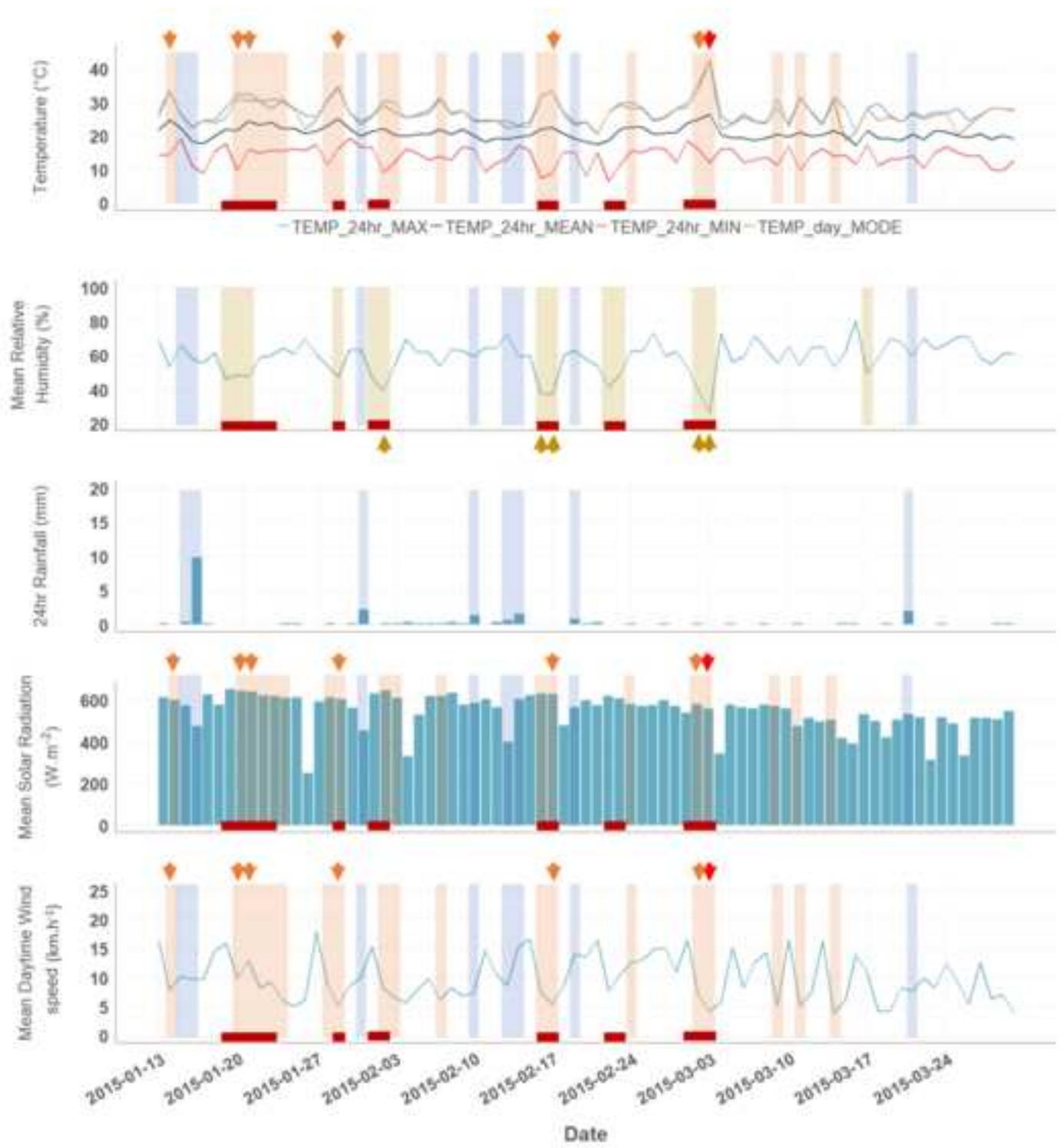


Figure 3

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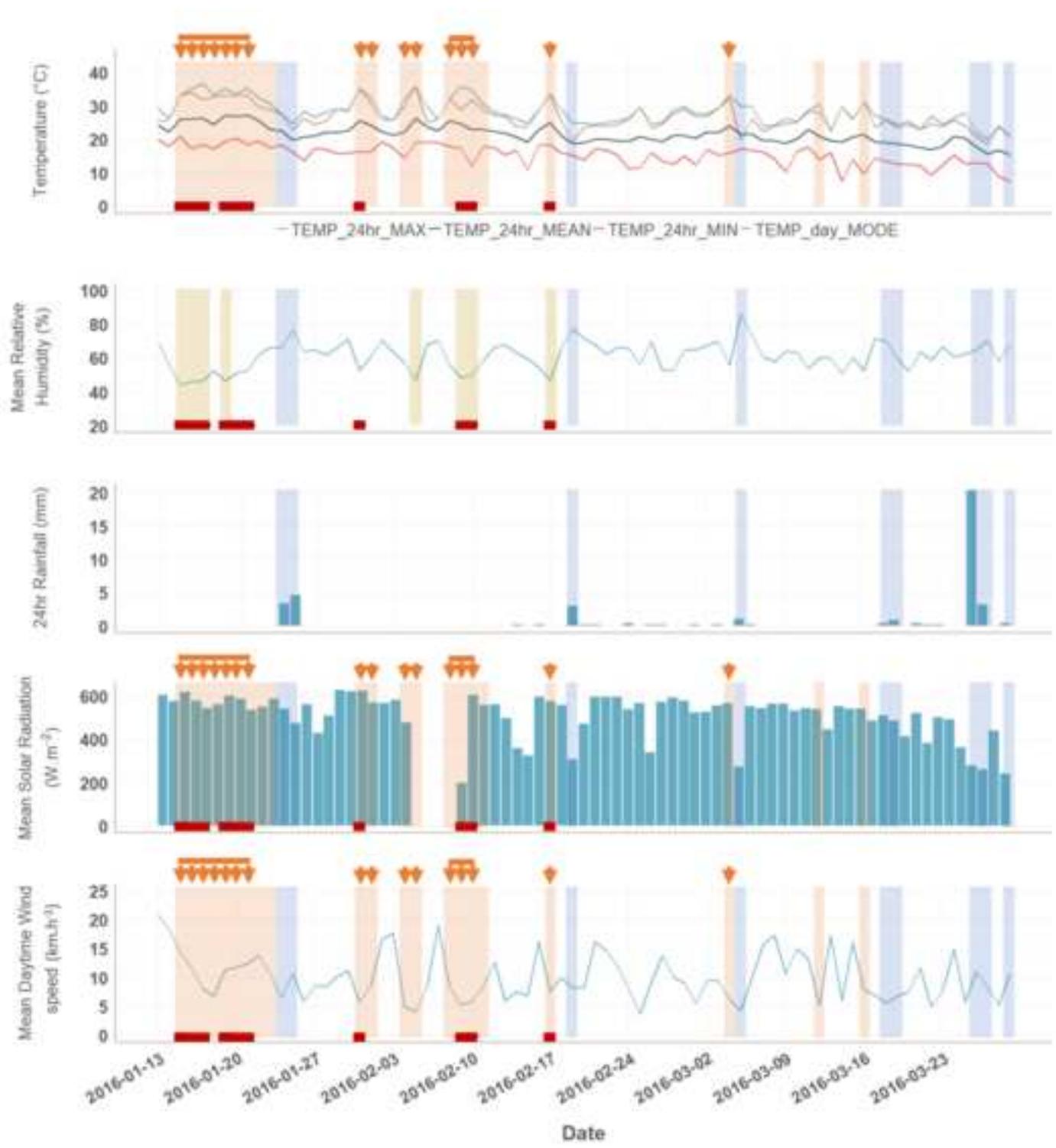


Figure 4
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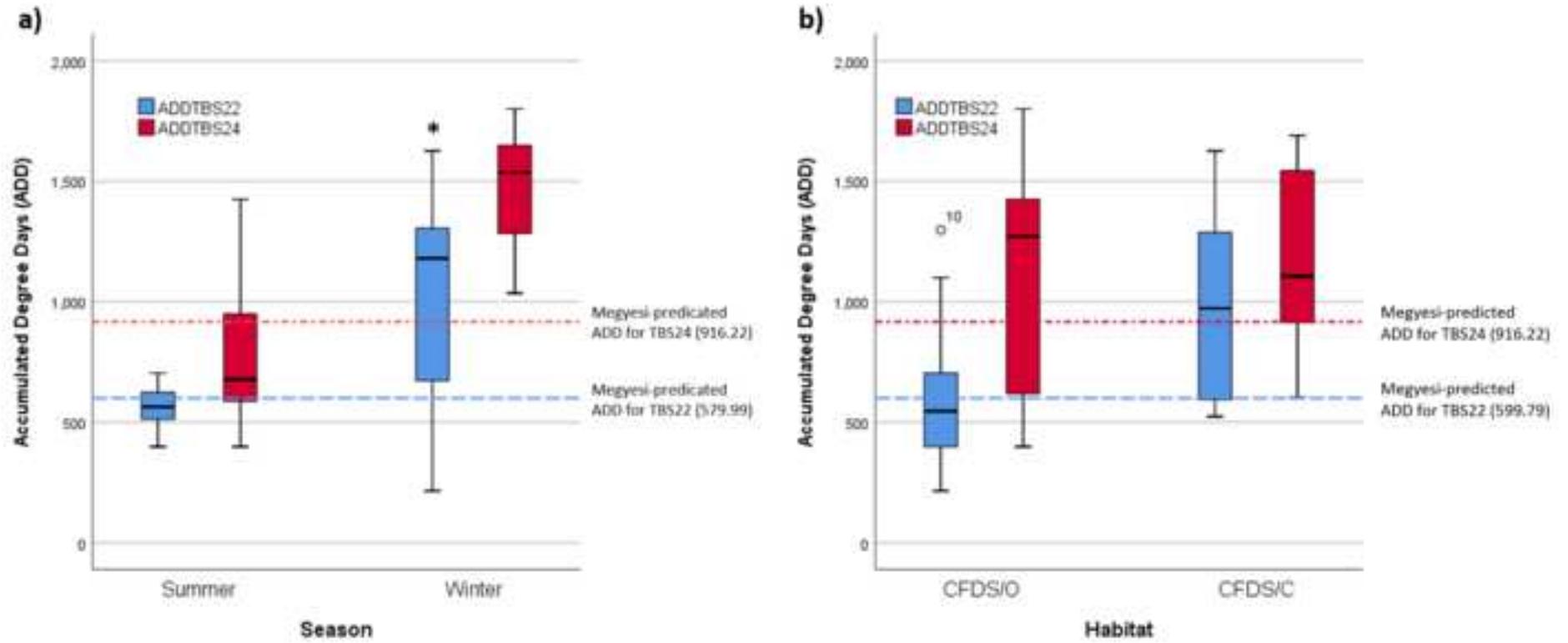
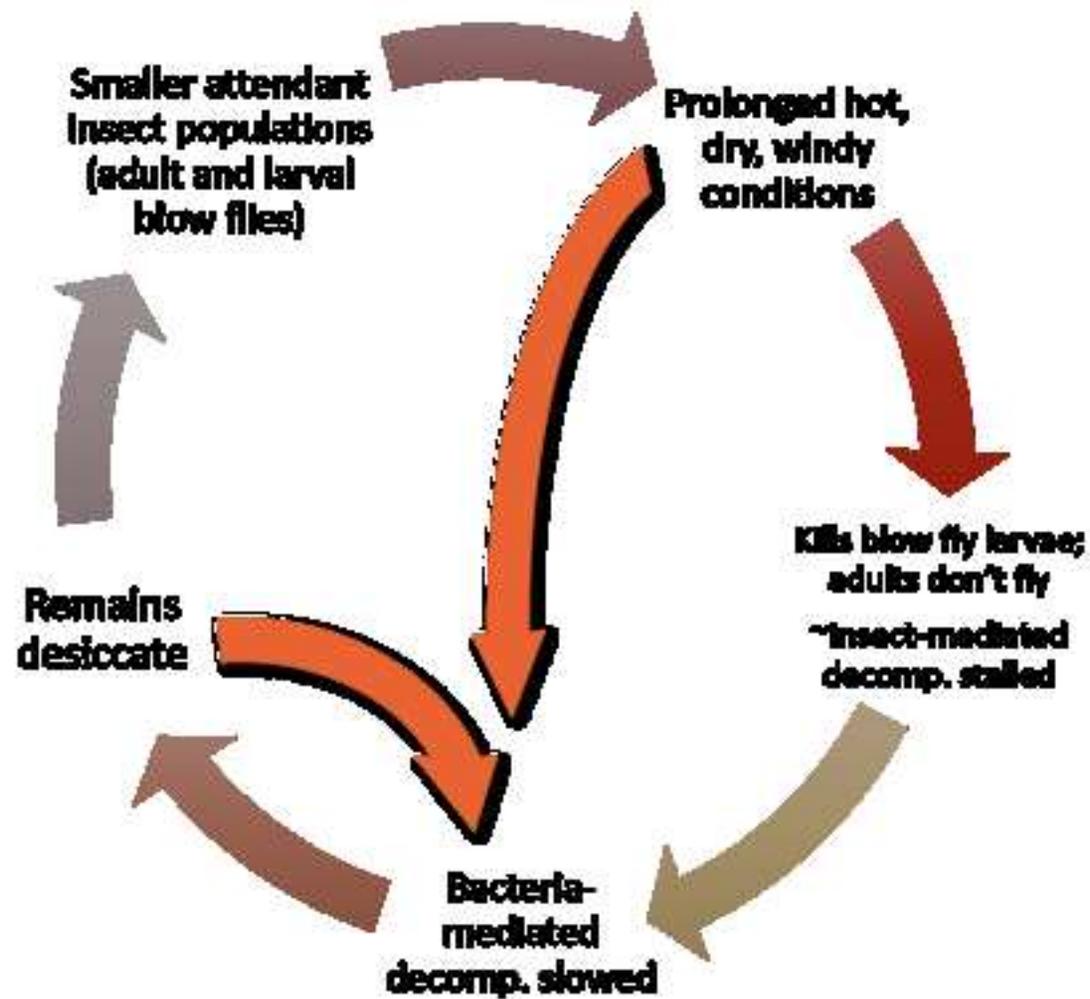


Figure 5
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LT₅₀
Summer species

47.5°C



Lucilia eximia

48.8°C



Chrysomya albiceps

50.1°C



C. marginalis

Figure 6
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Figure 2. Temperature (ambient; 24hr maximum, minimum and mean, daytime modal), relative humidity (%), 24hr rainfall (mm), mean solar radiation (W.m^{-2}), and mean daytime wind speed data (km.h^{-1}) for Cycle 2 (S-2015). Seven hot days are indicated with , one heat spike is indicated with , six cold fronts are highlighted with , 19 days with a maximum ambient temperature $> 30^{\circ}\text{C}$ are highlighted with , five dry days are indicated with , 13 days with mean daytime humidity $< 50\%$ are highlighted with ; six spells with drought-like conditions are indicated with  (the length of which indicates duration).

Figure 3. Temperature (ambient; 24hr maximum, minimum and mean, daytime modal), relative humidity (%), 24hr rainfall (mm), mean solar radiation (W.m^{-2}), and mean daytime wind speed data (km.h^{-1}) for Cycle 4 (S-2016). 16 hot days are indicated with , two hot spells are denoted by  (the length of which indicates duration), six cold fronts are highlighted with , 21 days with a maximum ambient temperature $> 30^{\circ}\text{C}$ are highlighted with , eight days with mean daytime humidity $< 50\%$ are highlighted with ; five spells with drought-like conditions are indicated with  (the length of which indicates duration).

Figure 4

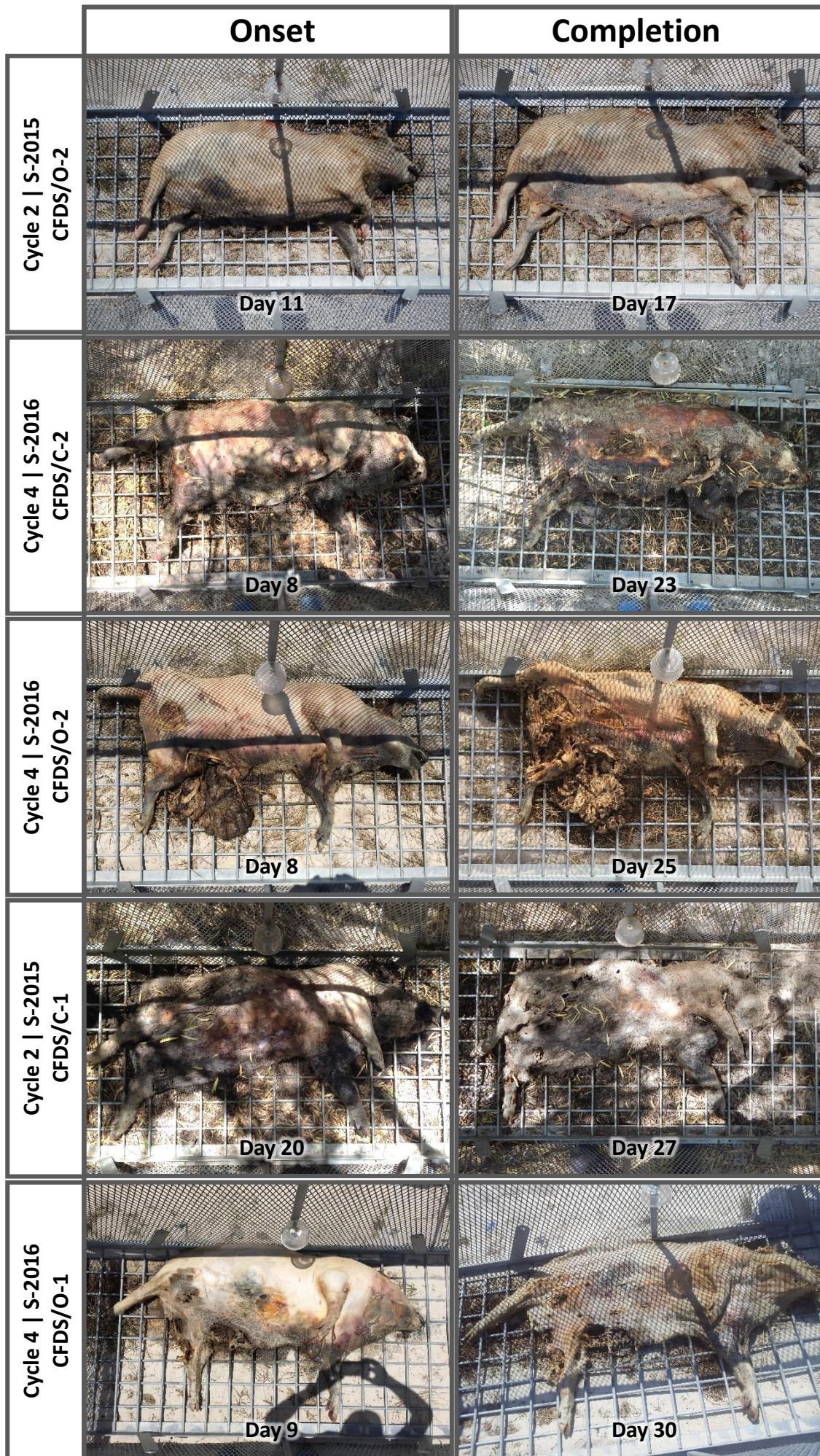


Table 1: Time (in 24-hour days) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing season.

		Summer (n=8)	Winter (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median	20.50	92.00	49.50	11.344	*0.001
	(IQR)	(3.00)	(25.00)	(72.00)		
	(Range)	(17-26)	(73-112)	(17-112)		
Onset of mummification (this study)	Median	12.50	65.50	34.50	11.344	*0.001
	(IQR)	(11.00)	(14.00)	(55.00)		
	(Range)	(8-20)	(49-75)	(8-75)		
Completion of mummification (Megyesi)	Median	28.50	109.50	72.00	11.311	*0.001
	(IQR)	(23.00)	(19.00)	(84.00)		
	(Range)	(17-67)	(77-124)	(17-124)		

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

Table 2: Time (in 24-hour days) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing habitat.

		CFDS/O (n=8)	CFDS/C (n=8)	TOTAL (N=16)	<i>H</i> (1)	<i>p</i> -value
Onset of mummification (Megyesi)	Median	52.00	49.50	49.50	0.335	0.563
	(IQR)	(71.00)	(79.00)	(72.00)		
	(Range)	(17-112)	(20-112)	(17-112)		
Onset of mummification (this study)	Median	31.50	41.00	34.50	0.543	0.461
	(IQR)	(54.00)	(50.00)	(55.00)		
	(Range)	(8-68)	(8-75)	(8-75)		
Completion of mummification (Megyesi)	Median	70.88	68.13	72.00	0.003	0.958
	(IQR)	(83.00)	(83.00)	(84.00)		
	(Range)	(17-124)	(23-115)	(17-124)		

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis; *p*-value significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

Table 3: Accumulated Degree Days (ADD) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing season.

		Summer (n=8)	Winter (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median	564.27	1179.96	791.24	2.824	0.093
	(IQR)	(126.24)	(787.17)	(712.60)		
	Range	397.84-703.69	214.86-1410.94	214.86-1625.80		
Onset of mummification (this study)	Median	295.07	725.89	422.09	2.828	0.093
	(IQR)	(203.02)	(579.59)	(527.60)		
	Range	230.78-458.58	139.13-1003.78	139.13-1003.78		
Completion of mummification (Megyesi)	Median	677.44	1536.48	1188.61	8.647	*0.003
	(IQR)	(449.88)	(391.10)	(916.38)		
	Range	397.84-1425.28	1035.18-1800.43	397.84-1800.43		

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

Table 4: Accumulated Degree Days (ADD) to onset and completion (~totality) of mummification per Megyesi and colleagues' [1] and this study's definitions, comparing habitat.

		CFDS/O (n=8)	CFDS/C (n=8)	TOTAL (N=16)	H(1)	p-value
Onset of mummification (Megyesi)	Median	545.79	972.43	623.81	2.692	*0.007
	(IQR)	(516.52)	(731.12)	(712.60)		
	Range	214.86-1297.40	523.75-1625.80	214.86-1625.80		
Onset of mummification (this study)	Median	256.38	803.94	422.09	7.296	0.101
	(IQR)	(271.72)	(418.88)	(527.60)		
	Range	139.13-647.83	385.59-1003.78	139.13-1003.78		
Completion of mummification (Megyesi)	Median	1271.15	1106.07	1188.61	0.339	0.560
	(IQR)	(914.72)	(813.17)	(916.38)		
	Range	397.84-1800.43	603.88-1689.39	397.84-1800.43		

H statistic from Kruskal-Wallis test for nonparametric data, with degrees of freedom denoted in parenthesis **p-value** significant when $p < 0.05$ and is denoted by **bold** type and an asterisk (*).

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CRedit author statement

Devin Finaughty: Conceptualization, methodology, project administration, investigation, data curation, formal analysis, software, visualization, writing- original draft, funding acquisition.

Alan Morris: Supervision, resources, writing- reviewing and editing, funding acquisition.