Inaccuracy of accumulated degree day models for estimating terrestrial post-mortem intervals in Cape Town, South Africa

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Abstract

In forensic death investigations, estimating the postmortem interval (PMI) is critical. An accurate PMI estimate increases the speed and accuracy of identifying the remains by narrowing the time frame in which the death occurred, thus reducing the pool of possible decedents. Cape Town, South Africa has a high level of unnatural death, and due to a burdened death investigation system, many remain unidentified. There has been a tendency to broadly apply quantitative models of decomposition across biogeographically unique circumstances. A prime example is the widespread application of the total body score (TBS)/accumulated degree day (ADD) model developed by Megyesi et al. (2005), later refined by Moffatt et al. (2016). However, the appropriateness of applying a single model to a wide range of locations with unique geography and climates remains in question. The aim of the study was to evaluate and compare the accuracy of Megyesi and Moffatt models for estimating PMI in Cape Town, South Africa. Using pig carcasses, ~~Author 2~~Finaughty established baseline data on the rates and patterns of terrestrial decomposition in summer and winter in two different locations in a forensically significant area of Cape Town. Among the baseline data, ~~Author 2~~Finaughty derived TBS values using the Megyesi criteria. The present study used these values to estimate the ADD per the Megyesi and Moffatt models, which would correspond to an estimated PMI. These estimated values were compared to ~~the~~ actual ADD values. Estimates of ADD were inaccurate for both models in winter, and only partially in summer. The Moffatt model was more accurate in ~~the~~ earlier decomposition stages, with the Megyesi model more accurate in later decomposition stages. These results indicate the Cape Town environments may contain factors that the two models do not consider, producing inaccurate PMI estimations at various TBS~~'~~’ values. ADD does not depict the entire taphonomic story; the decomposition process appears to be too complex for universal modelling based on a single or narrow suite of variables. Seasonality was an important factor in determining the accuracy of the models, primarily resulting in underestimations of the true PMI values. These findings show the impracticality of applying models developed for- or in one region to any other and support the need to establish regionally-specific equations for estimating PMI in a forensic context. Alternatively, more complex models employing ~~"big data"~~“big data” from a more comprehensive suite of variables which influence the rate and pattern of decay could be developed.

Keywords: Accumulated degree days; Decomposition; Total body score; Forensic taphonomy; Postmortem interval

1 Introduction

In forensic death investigations, estimating the postmortem interval (PMI), or time~~-~~-since~~-~~-death, is critical. An accurate PMI estimate increases the speed and accuracy of identifying the remains by narrowing the time~~-~~-frame ~~in which~~when the death occurred, thus reducing the pool of possible decedents. Forensic anthropologists typically encounter remains in advanced decomposition, or a skeletonised state, necessitating the development of a model that can quantify the postmortem interval (PMI) over longer time ~~periods~~intervals. To estimate PMI, Megyesi et al. [1] developed a universal model to translate qualitative observations of decay into a quantitative measure, known as the total body scoring (TBS) system. Using this method, approximately 80% of the observed variation in the decomposition process was attributable to thermal energy, measured by ‘accumulated degree days (ADD)’ ~~-~~— the sum of thermal energy accrued over a period of time. This quantitative method of predicting the PMI based on the visual assessment of decomposition and its relationship to temperature has since become one of the most commonly used approaches for researchers and law enforcement personnel worldwide [2–11]. However, several studies have reported results that differ significantly between the actual ADD and calculated ADD based on TBS values [5,8,12,13].

Moffatt et al. [14] identified several statistical errors in the Megyesi et al. [1] formula; a key error being when they interchanged the independent (ADD) and dependent (TBS) variables. Due to the inherently different properties of dependent and independent variables in a linear regression, switching the values produces an incorrect slope, thus, invalidating the model. Moffatt et al. [14] also showed that rounding off an exponent value affects the calculated value, thus, reducing the significant figures of the exponent to one in the regression slope, resulting in overestimation of the calculated ADD value. These errors were corrected in a refined equation by Moffatt et al. [14]. However, based on a review of the published literature, this new model has yet to be validated.

The accuracy of global models ~~of~~ for PMI estimation needs to be addressed, which is more apparent in regions where forensic investigations are common. South Africa has one of the highest murder rates in the world [15]. In 2017/18, 20,336 homicides were recorded, which is a rate of 35.7/100,000 people, or 57 people per day [16]. The need to understand how localized factors affect the decomposition process can be even greater in smaller geographical areas. The Western Cape province in South Africa includes the city of Cape Town, which is labelled as ‘the murder capital of South Africa’ with 3729 homicides (56.3/100,000 people) in 2017/18 [16].

In southern Africa, published decomposition studies have been conducted in two cities, Pretoria [5,6,17], and Bloemfontein [18–21], representing the ~~H~~highveld grassland biome, but are lacking in other major urban centres, particularly in Cape Town. This is especially relevant given Cape Town’s high homicide rate, where many homicide victims remain unidentified [16,22–24], and its biogeographical uniqueness. The aim of this study was to evaluate and compare the accuracy of two existing models (Megyesi et al. [1] and Moffatt et al. [14]) for estimating PMI in Cape Town, South Africa. In this study, both the Megyesi et al. [1] and Moffatt et al. [14] models are assessed using porcine proxy trials in a warm temperate climate characterized by hot, dry summers (Csb on the Köppen~~-~~–Geiger climate classification; [25,26]) in Cape Town, South Africa. PMI data from Cape Town is also compared with published data from Pretoria, Gauteng province, a city 1~~500 kilometres~~500 km inland. Due to Cape Town’s unique biogeoclimatic circumstance it is expected that the Megyesi et al. [1] and Moffatt et al. [14] models will be inaccurate in estimating PMI.

2 Materials and methods

2.1 Study location

Experiments were conducted by ~~Author 2~~Finaughty within the Cape Flats Dune Strandveld (CFDS) vegetative habitat at the South African Medical Research Council’s Animal Unit (33.916385 °S/18.604458 °E) in Delft, Cape Town, South Africa [27]. This habitat covers a region of the City of Cape Town Metropole with relatively high human density (~~i.e. 1,~~i.e. 1530 people/km²; [28]), and represents sites where disposed human bodies are frequently found~~.~~ (Fig. 1).

The CFDS habitat is open shrubland and is often colonized by invasive grass species (Poaceae sp.); it provides little canopy cover as most of the vegetation is within the low-lying shrub layer. However, alien vegetative species, particularly Port Jackson (*Acacia saligna*) and Rooikrans (*Acacia cyclops*), have become the dominant species in many of these habitats, and provide dense thickets of cover. Accordingly, two microhabitats fell under study: open CFDS (CFDS/O) and closed (heavily vegetated) CFDS (CFDS/C).

The climate in this region is characterized by hot summers (averaging 23 °C), with thermal extremes of >45 °C possible. These are often accompanied by strong Southeaster trade-winds [29~~], HYPERLINK \l "Ref30" \o "[30] Van der Velden. 2017. Cape Town: Four Seasons in One Day. Cape Town Magazine. https://www.capetownmagazine.com/seasons-cape-town." \h 30~~ ,30]. The region experiences mild winters ($\bar{x}$ 13 °C), with temperatures rarely <0 °C. Seasons are defined as winter (June~~-~~–August), and summer (November~~–~~–February). The average monthly rainfall in winter is between 88 mm and 105 mm, and between 10 mm and 25 mm in summer [31]. Most rain falls in the winter due to cyclonic fronts and the associated northwesterly winds.

2.2 Pig carcasses

The Megyesi et al. [1] and Moffatt et al. [14] models were designed using human references, but we tested them using pigs as proxies. A study by Keough et al. [32] analyzed the decomposition differences between pigs and humans. They found the same bacterial, insect, and vertebrate decomposers act on both species, suggesting that the results are similar enough to be informative in a forensic context where baseline data, such as that being established in the current study, are concerned. This has been affirmed in recent studies examining the differences in the rate and pattern of decomposition between simultaneously decomposing pig, human, and rabbit subjects [33,34].

(We have added two additional references (33 & 34). I tried to add them into the References section but could not. They are as follows: [33] Connor, M., Baigent, C. & Hansen, E.S. 2018. Testing the use of pigs as human proxies in decomposition studies. *Journal of Forensic Sciences*. 63(5):1350–1355. DOI: 10.1111/1556-4029.13727.
[34] Dautartas, A., Kenyhercz, M.W., Vidoli, G.M., Meadows Jantz, L., Mundorff, A. & Steadman, D.W. 2018. Differential decomposition among pig, rabbit, and human remains. *Journal of Forensic Sciences*. 63(6). DOI: 10.1111/1556-4029.13784.)

~~Author 2~~Finaughty used a total of 16 adult domestic pig carcasses purchased from Stellenbosch University’s Piggery Unit at the Mariendahl Experimental Farm ~~that~~. Note that the term “carcass” (and the plural “carcasses”) as used hereafter refers to pig carcasses only. The pigs were humanely euthanized using ear-to-ear stunning and a single gunshot to the base of the brain with a 0.22 caliber rifle in quick succession, shortly after sunrise (University of Cape Town’s

Faculty of Health Sciences Animal Ethics Committee AEC REF NO: 014/004). Carcasses were placed into body bags immediately post-euthanasia and transported to the research site. A single male and female pig were placed in each habitat within two hours of death, in individual 2 m ~~x 0.9 m x~~ × 0.9 m × 0.9 m custom-made steel wire cages containing a weighing grid. Only pigs within a certain range for weight, length, width, height, and sub-cutaneous fat thickness were selected for this study, so none differed significantly. Pig measurements were: body weight ($\bar{x}$ 63.5 kg 0.88 S.E.; range 55~~-~~–63.5 kg); length ($\bar{x}$ 122.00 cm, 0.92 S.E.); width ($\bar{x}$ 29.82 cm, 1.03 S.E.), stature height ($\bar{x}$ 55.09 cm, 0.42 S.E.), and subcutaneous fat depth ($\bar{x}$ 6.38 mm, 0.20 S.E.).

~~Author 2~~Finaughty established two 11.6 m² experimental plots in each habitat, spaced a minimum of 35 m apart to prevent cross-contamination of crawling insects. Vegetative cover, moisture, wind, and soil type were similar for each plot within their respective habitats. A pig was placed on each experimental plot for every experimental cycle (1 cycle = 1 season). Data were collected over four experimental cycles; both summer cycles occurred over 77 days respectively, and the winter cycles each occurred over 142 days.

2.3 Scoring decomposition

The state of decomposition of the pigs was visually assessed and recorded by ~~Author 2~~Finaughty following Megyesi et al.'s [1] criteria and assigned a total body score (TBS). TBS values were collected at regular intervals during the various decomposition stages and ended when all carcasses reached skeletonization. Adlam and Simmons' [2] skeletonization criteria were used to determine the end for each decomposition cycle, as they use a more comprehensive definition.

For analyses in this study, only those sampling events with TBS values of 12, 14, 18, and 22 were selected because they represent the scores most frequently recorded across all 16 carcasses; the TBS scores of 12, 18, and 22 were recorded on 13 pigs, and TBS 14 was recorded on 12 pigs.

Average daily ambient temperatures were obtained from a wireless Vantage Pro 2 weather station (Davis Instruments, Hayward, California) at each habitat site. Daily mean air temperature (°C) was derived by combining maximum and minimum air temperatures and dividing by two for each day of data collection. The ADD data were obtained through the summation of daily mean temperatures of the habitats from the date of placement until the end of the cycle period.

Known ADD values ($\mathrm{ADD_{actual}}$) to the estimated ADD values were calculated from the Megyesi et al. [1] model ($\mathrm{ADD_{Meg}}$):

$$\left(\mathrm{ADD_{Meg}} = 10^{(0.002*\mathrm{TBS}*\mathrm{TBS}+1.81)} \pm 388.16\right);$$

and the refined Moffatt et al. [14] model ($\mathrm{ADD_{Mof}}$):

$$\left(\mathrm{ADD_{Mof}} = 10^{\left(\frac{\mathrm{TBS}+212}{125}\right)}\right).$$

$\mathrm{ADD_{actual}}$ values were calculated by summing the daily temperature averages for each carcass and $\mathrm{ADD_{Meg}}$ and $\mathrm{ADD_{Mof}}$ were calculated from specific TBS values (12, 14, 18, 22).

2.4 Statistical analyses

All statistical analyses were performed using R [33]. Statistical significance was considered at $p \le 0.05$. Analysis of Variance (ANOVA) was performed on the whole data set to assess any biases ~~which~~ that may arise within the sample. The following variables were assessed in this manner: pig sex (males and females), habitat (CFDS/O and CFDS/C), and season (summer and winter) with respect to ADD values at each TBS. One-sample t-tests were used to test whether the Megyesi et al. [1] and Moffatt et al. [14] models accurately estimate $\mathrm{ADD_{actual}}$. Due to lack of variability within $\mathrm{ADD_{Meg}}$ and $\mathrm{ADD_{Mof}}$ datasets, one-sample t-tests were appropriate. We present results from the pooled sample initially. Given the results of bias identification, data were separated and analysed within sub-groups (season and habitat).

3 Results

For all four TBS values, there were no statistically significant differences between ADD values with respect to sex or habitat (Table 1). However, there were differences between the summer $\mathrm{ADD_{actual}}$ values and the winter $\mathrm{ADD_{actual}}$ values. The data were subdivided by season and analyzed using one-sample t-tests as a measure of specific differences between individual parameters and the Megyesi et al. [1] and Moffatt et al. [14] models.

Table 1 Statistical ANOVA results for confounding variable within actual dataset by sex, habitat, and season for ADD values at TBS 12,14,18, and 22.

alt-text: Table 1

TBS	Factor	df	Sum of ~~SquaresMean S~~squares	Mean squares	F-ratio	*p*-Value

12	Sex	1	2450	2450	3.4591	0.0925
	Habitat	1	205	205	0.2900	0.6020
	Season	1	37698	37698	53.2146	**<0.001**
	Residuals	10	7084	708		
14	Sex	1	6035	6035	2.1757	0.1743
	Habitat	1	34	34	0.0123	0.9140
	Season	1	104165	104165	37.5525	**<0.001**
	Residuals	9	24965	2774		
18	Sex	1	3997	3997	0.3616	0.5610
	Habitat	1	51861	51861	4.6917	0.0555
	Season	1	1002923	1002923	90.7315	**<0.001**
	Residuals	10	110537	11054		
22	Sex	1	11994	11994	0.7916	0.3945
	Habitat	1	71895	71895	4.7449	0.0544
	Season	1	1671762	1671762	110.3316	**<0.001**
	Residuals	10	151522	15152		

Items in **bold** were statistically significant ($p \leq 0.05$). TBS = total body score; df = degrees of freedom.

All results are presented as the difference between the actual ADD value and the predicted using the Megyesi et al. [1] and Moffatt et al. [14] models. If the difference is positive it means the model has underestimated the actual ADD, and if negative the actual ADD is overestimated by the model.

Preliminary one-sample t-tests of the combined data indicated that the Megyesi et al. [1] estimated ADD was similar at TBS 12 and 18, but significantly different at TBS 14 and 22 (Table 2). Using the Moffatt et al. [14] model, the four estimated ADD values were significantly different than the actual. Overall, the Megyesi et al. [1] ADD and the Moffatt et al. [14] ADD models underestimated the actual ADD ~~(Fig. 1)~~.

Table 2 Comparison of mean actual ADD values ~~versus Megyesi et al. (2005)~~Megyesi et al. [1] ADD and Moffatt et al. ~~(2016)~~[14] ADD values at TBS 12, 14, 18, and 22, showing combined data, and data split by habitat and season. Percentage difference between actual ADD and Megyesi ADD, and actual ADD and Moffatt ADD are indicated.

alt-text: Table 2

TBS	ADD_{actual}	ADD_{Meg}	%diff	ADD_{Mof}	%diff
Combined data					
12	140.73	125.31	11.59	92	**41.88**
14	253.66	159.22	**45.75**	116	**74.48**
18	456.57	287.08	45.58	201	**77.73**
22	938.76	599.79	**44.06**	383	**84.09**

TBS	ADD_{actual}	ADD_{Meg}	%diff	ADD_{Mof}	%diff	ADD_{actual}	ADD_{Meg}	%diff	ADD_{Mof}	%diff
CFDS Open Summer						CFDS Closed Summer				

12	77.42	125.31	**47.25**	92	17.21	95.18	125.31	27.33	92	3.40
14	133.61	159.22	17.49	116	14.11	165.3	159.22	3.75	116	35.05
18	194.96	287.08	38.22	201	3.05	243.50	287.08	16.43	201	19.12
22	631.07	599.79	5.08	383	**48.93**	553.08	599.79	8.10	383	**36.34**
TBS	ADD_{actual}	ADD_{Meg}	%diff	ADD_{Mof}	%diff	ADD_{actual}	ADD_{Meg}	%diff	ADD_{Mof}	%diff
CFDS Open Winter						CFDS Closed Winter				
12	191.55	125.31	**41.81**	92	**70.21**	197.03	125.31	**44.50**	92	**72.68**
14	332.66	159.22	**70.52**	116	**96.58**	342.79	159.22	**73.13**	116	**115.36**
18	823.59	287.08	**96.61**	201	**121.53**	671.86	287.08	**80.25**	201	**107.89**
22	1294.93	599.79	**73.38**	383	**108.70**	1285.79	599.79	**72.76**	383	**108.20**

Items in bold were statistically significant ($p \leq 0.05$). TBS = total body score; ADD_{actual} = actual accumulated degree days; ADD_{Meg} = estimated accumulated degree days using Megyesi et al. ~~2005~~[1] model; ADD_{Mof} = estimated accumulated degree days using Moffatt et al. ~~2016~~[14] model; CFDS = Cape Flats Dune Strandveld habitat.

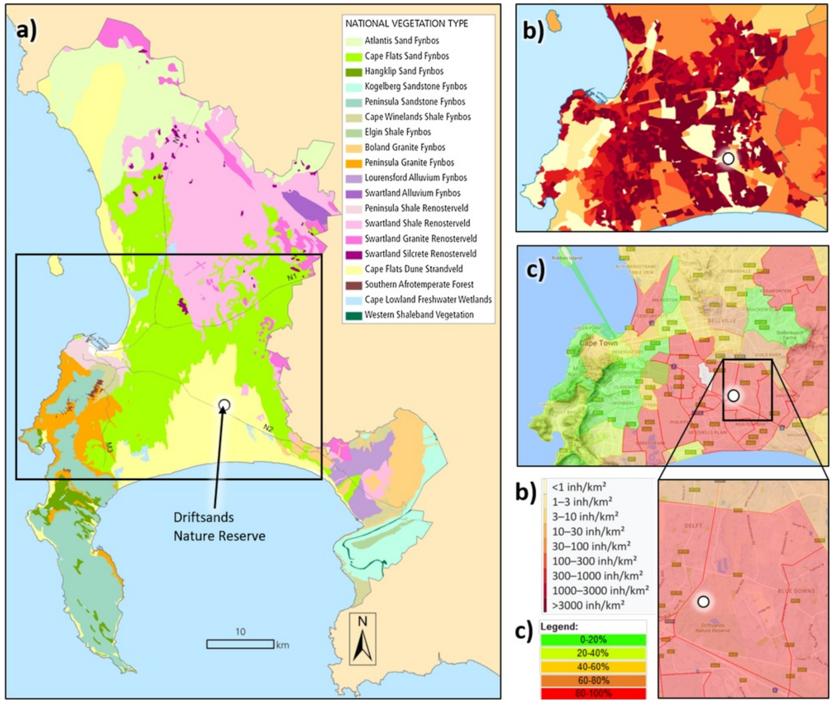

Fig. 1 (a) Vegetation subtypes of the City of Cape Town Metropole. Location of Driftsands Nature Reserve is indicated. Area of interest for (b) and (c) is highlighted. (b) Population density of the City of Cape Town Metropole, measured by inhabitants/square kilometre (inh/km2) (Htonl, 2015). Legend is indicated below. (c) Heat map of the City of Cape Town Metropole indicating quintiles of contact crimes (murders) per police precinct. Precincts within the fifth quintile (top 20%) in terms of number of murders are indicated in red. Legend is indicated below. The precinct the research site is in (Mfuleni) is enlarged in the inset, with 195 murders in this precinct during 2017/18 (SAPS, 2018). From Spies et al. (2018a; 2018b) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

alt-text: Fig. 1

3.1 Separation by season & habitat

With respect to ADD values at each TBS, significant differences were shown between seasons. Using both the Megyesi et al. [1] and Moffatt et al. [14] models, in winter for all TBS the differences between the actual ADD and estimated were significantly underestimated (Fig. 2). The difference from actual ADD increased as decomposition (TBS scores) advanced. These results were consistent in both the closed and open habitats (CFDS/O and CFDS/C; Table 2). These results show that neither model was reliable for winter. In summer, while the Megyesi et al. [1] model showed significant differences at TBS 12 and 18, all four differences overestimated actual ADD. The Moffatt et al. [14] model overestimated the ADD at TBS 12, but underestimated ADD at TBS 14, 18, and 22. In summer, the Megyesi et al. [1] model initially overestimated the actual ADD at TBS 12, and then underestimated the actual ADD at the larger TBS scores.

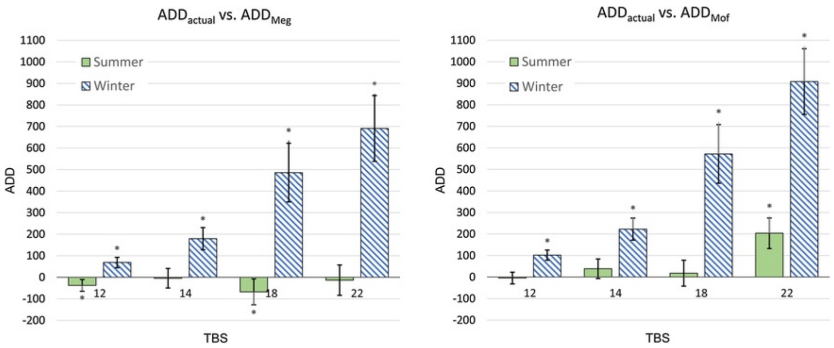

Fig. 2 Applying the Megyesi et al. ~~(2005)~~[1] model and the Moffatt et al. ~~(2016)~~[14] model to assess the difference between mean actual ADD and mean Megyesi/Moffatt ADD at TBS 12, 14, 18, and 22 during the summer and winter seasons. Differences were calculated by subtracting the mean Megyesi/Moffatt ADD from mean actual ADD. Significance ($p \leq 0.05$) is denoted by the asterisk.

alt-text: Fig. 2

Using the Megyesi et al. [1] model in the CFDS/O habitat, differences between the actual ADD and estimated were significantly different for TBS 12 in summer where ADD was overestimated (Table 2). At TBS 12, 14, and 18 ADD were considerably overestimated. In the CFDS/C habitat, no significant differences were observed between the actual ADD and estimated. The differences between the actual ADD and estimates for all TBS scores, except at TBS 14, were negative. This is because the estimated ADD were larger than the actual ADD.

Using the Moffatt et al. [14] model in the CFDS/O habitat, a significant difference was detected at TBS 22, overestimating ADD during summer (Table 2). However, it was underestimated at TBS 12 and 18, and overestimated at TBS 14 and 22. In the CFDS/C habitat, the difference between the actual and estimated ADD was significant for TBS 22, and this model consistently underestimated actual ADD.

4 Discussion

Globally, the application of ADD to estimate PMI has become a popular technique amongst forensic anthropologists. Applications of global models are attractive to investigators to negate the need for conducting expensive and time-consuming research on decomposition in every local environment. However, evidence is growing that global models do not incorporate enough ~~of the~~ biogeoclimatic variation to adequately capture decomposition rates in different regions.

In this study, there were no statistically significant differences between carcass sex or habitat with respect to ADD values at each TBS, therefore, these factors do not appear to influence the results. A preliminary analysis of the entire dataset indicated that both models produced estimated ADD values that underestimated the actual carcass ADD at all evaluated TBS values. Megyesi et al.'s [1] model was more accurate in the earlier stages of decomposition (~~i.e.~~i.e. TBS 12) and then progressively decreased in accuracy with increasing TBS. The differences found using the Moffatt et al. [14] model were statistically significant at all TBS values, suggesting this model is not reliable in ~~this~~Cape Town's environment.

The results clearly show three distinct patterns amongst the seasons and the models: (1) the models were more accurate in the summer than the winter; (2) the Megyesi et al. [1] model was more reliable in later decomposition stages and (3) the Moffatt et al. [14] was more reliable in earlier decomposition stages. Each of these patterns are discussed below.

4.1 Summer vs. winter patterns W(Not sure what happened here. I tried to revise through the edit log but it would not work. Please double-check the words aren't duplicated (they appear so on my side; currently reads: "4.1 Summer vs. winter patterns Winter patterns"))inter patterns

First, both models performed better in the combined summer data than in the combined winter data, with fewer statistically significant results in summer, whereas all differences were significant in winter. These results were similar to the decomposition study conducted in Pretoria, South Africa [17]. The significant difference between seasons and variability in decomposition is likely due to a combination of factors, such as differences in insect activity, temperature, rainfall, and humidity, which vary by season. Myburgh [17] discovered that deriving separate equations for seasons resulted in a higher accuracy for estimating the PMI (76%~~-~~–80%)(76%–80%); this percentage range correlates with Megyesi et al. [1] conclusions and, therefore, validates the model in Pretoria. In 2013, Myburgh et al. [5] derived their own linear regression formula, but following validation it was determined that decomposition in Pretoria was too variable to accurately predict PMI using ADD and TBS. Therefore, it is unclear how well ADD can predict PMI in Pretoria, South Africa, and unfortunately the results from Cape Town are difficult to compare as linear regression formulae have not yet been developed. This is an area of possible expansion on these preliminary results.

4.2 Megyesi et al. [1] model

For the summer data, the Megyesi et al. [1] model was less reliable in the earlier decomposition stages but became more accurate as time progressed. The Megyesi et al. [1] ADD values were observed to both underestimate (avg. 17%) and overestimate (avg. 83%) the actual ADD. These findings support conclusions drawn from Marhoff et al. [8], and Parsons [34] who found that although the Megyesi et al. [1] ADD values consistently overestimated the actual ADD, the model became increasingly more accurate towards the end of their studies. However, not all studies support this finding.

Suckling [12] and Spencer [13] found the reverse trend, which may be due to the zero and sub-zero temperatures in these regions. Parsons' [34], Suckling's [12], and Spencer's [13] research were conducted in the cool temperate regions of North America (Dfb, Cfa, and Dfb, respectively, on the Köppen~~-~~–Geiger climate classification; [25,26]), where winters are typically cold, causing bodies to freeze and then thaw in spring, resulting in periods of stasis followed by accelerated post-thaw decomposition. This dormant period – an extreme instance of stasis – impacts PMI estimations. This may explain why the findings of these three studies differ from this study's results, as Cape Town is considered to have a warm temperate climate. Consideration for climatic differences in study comparisons is critical when evaluating seasonal decomposition data because many of the studies where the Megyesi et al. [1] model is inaccurate were conducted in areas that do not experience very cold temperatures [~~8,17~~8,17, this study]. The average daily temperature in Cape Town and Hawkesbury, Australia during the winter is 13 °C and 12 °C respectively, and very rarely reaches <0 °C at night [8,30,35]; thus, winter carcasses do not freeze. However, it is possible for bodies in these areas to enter prolonged stasis periods towards the end of decomposition if the body mummifies; as a result, mummification would most likely affect PMI estimations and potentially cause inaccuracies. Consequently, the findings of these five studies, including the current study, demonstrate that different environments have factors unaccounted for ~~in~~ by the Megyesi et al. [1] model.

4.3 Moffatt et al. [14] model

The Moffatt et al. [14] model was more accurate during the earlier decomposition stages represented by lower TBS values (TBS 12) and became progressively unreliable in advanced decomposition stages (TBS 22). As with the Megyesi et al. [1] model, the Moffatt et al. [14] model was ~~shown to be~~ wholly inaccurate for winter decomposition, thus, the following pattern is representative of the summer data only. As a rule, ADD will always start at zero as it cannot be represented as a negative value; therefore, when the actual ADD values are smaller in the fresh and active decay stages, they are closer to the estimated ADD produced by Moffatt et al. [14] model. These results indicate a clear pattern of model inaccuracy in the advanced decomposition stages as the differences between the estimated and actual ADD values at all TBS 22 values were significantly different. Finally, the results showed that the Moffatt et al. [14] ADD values both underestimated (avg. 75%) and overestimated (avg. 25%) the actual ADD. The reason for increased accuracy at the beginning of the decomposition could be how the model was developed, and its ability to produce lower ADD values than those produced using the Megyesi et al. [1] model at the same TBS.

4.4 Forensic implications

The utilization of multiple models of PMI estimation may yield more accurate PMI estimates. Based on our results and others who have questioned the validity of global models [12,17,34], it may be beneficial for those in forensic practice to assess the value of applying more than one model across biogeographic regions that vary greatly in the factors that influence decomposition rates. For instance, the Moffatt et al. [14] model was more reliable in earlier~~ decomposition stages~~, and the Megyesi et al. [1] model in later decomposition stages. However, there was considerable overlap in accuracy between the two models during the late active and early advanced stages.

It is important to note that the ADD method has inherent problems in its development and application. First, the TBS scoring method is subjective; it is broad and ambiguous in its descriptions of decompositional patterns, which may lead to inter-observer error when scoring carcasses. Several studies [17,36] have recorded a small inter-observer error when using the ADD method. However, observers were trained by the same person, which could be a problem if there was a lack of independent interpretation. Second, the Megyesi et al. [1] model uses an 80% confidence interval, which creates a large standard error of ± 388.16 ADD. This means that if the body is not scored properly, the PMI estimation could be weeks to months off the actual PMI, an error that would critically impact the forensic investigation. Finally, Megyesi et al. [1] defines skeletonization as exposure of >50% of bone. This definition is problematic as it does not consider variation in the presentation of skeletonisation. For example, in the hot and dry summers characteristic of this study area in Cape Town, the skin will mummify largely intact and the bones dry out beneath the skin, meaning bone exposure may be minimal even though the carcass is essentially skeletonised. Therefore, using more inclusive criteria of skeletonization is better [4].

In addition to the issues raised above, the Megyesi et al. [1] and Moffatt et al. [14] models are based only on temperature, even though many other factors influence decomposition [37–42]. ADD is useful for translating qualitative measures of decay into quantitative data to improve method reliability, but it does not depict the entire taphonomic story. The authors that created these equations attempted to make them useful for a wide range of geographical regions, unfortunately the decomposition process appears to be too complex for universal modelling based on a single or narrow suite of variables. To resolve these issues, it may be more appropriate to derive regionally specific formulae, using revised region-specific criteria that capture the nuances of decomposition in these habitats. Alternatively, more complex models employing “big data” from a more comprehensive suite of variables ~~which~~ that influence the rate and pattern of decay could be developed.

In conclusion, this study investigated the usability of the Megyesi et al. [1] and Moffatt et al. [14] models to predict PMI in Cape Town, South Africa. On validation, it was found that seasonality was an important factor in determining the accuracy of the models, primarily resulting in underestimations of the true PMI values. These findings support the need to establish regionally-specific equations for estimating PMI in a forensic context. Future research should aim to establish regression formulae for winter and summer seasons in Cape Town, which can be validated using local forensic case work where bodies with known PMI are analyzed.

Declarations of interest

None.

Grant declaration

The financial assistance of the South African National Research Foundation (NRF) towards this research is hereby acknowledged (grant no. ~~87805~~87805). Opinions expressed & conclusions arrived at, are those of the authors and are not necessarily to be attributed to the NRF.

Acknowledgments

We thank Dr. R. Malenfant and Mr. S. Randall for their statistical expertise and the Department of Human Biology, University of Cape Town. This study would not have been possible without those who supported Finaughty’s Ph.D. project: Prof. A.G. Morris (Supervisor); Dr. C. de Villiers MRC’s Animal Unit Facility and for her team’s assistance; Mr. C. Harris and his team for construction of experimental apparatus; Mr. J Morris for pig carcasses; Dr. M Heyns and Mrs. J. Conradie of CSI Forensics for assisting with carcass transport; Mrs. C. Finaughty and Mrs. R. Logston for field assistance; Mrs. C. Bloch for processing the weather records.

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Highlights

- The accuracy of applying accumulated degree day models to various biogeoclimatic regions remains in question.

- Seasonality appears to have a large influence over the accuracy of the models in Cape Town.
- Moffatt et al. (2016) model was more accurate during the early stages of decomposition.
- Megyesi et al. (2005) model was more accurate during the advanced stages of decomposition.
- ~~Obtained data support t~~The need to establish regionally-specific ADD formulae for post-mortem interval estimations in forensic contexts is clear.