

A Comparison of Human and Domestic Pig Decomposition Using
Multivariate Methods

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ABSTRACT

Animal proxies are frequently used to substitute for human remains in decomposition studies. Domestic pigs have become the most commonly used nonhuman proxy due to an assumed similarity in decomposition progression to humans. This dissertation directly compares decomposition patterns along morphological indicators, insect activity and scavenging to assess if decomposition between humans and domestic pigs is similar enough such that data produced from a pig model can accurately predict human patterns. This study examines 15 human donors to 15 domestic pigs across three seasons. The data are analyzed with multivariate methods, including hierarchical linear modeling and dynamic linear regression time series analysis. The results of this study suggest that when examining decomposition as an entire complex process, patterns differ between domestic pigs and humans. Individual similarities in specific variables do exist, but the overall patterns differ between species to an extent that pigs cannot substitute for humans in all taphonomic and decomposition research, especially where the goal is to improve estimations of the postmortem interval.

TABLE OF CONTENTS

Chapter I. Introduction.....	1
Research goals and hypotheses	9
Hypotheses	10
Chapter II. Soft Tissue Decomposition.....	13
Fresh stage	14
Autolysis	14
Rigor mortis.....	14
Livor mortis.....	15
Algor mortis	15
Putrefaction.....	16
Active decomposition.....	17
Factors affecting the rates of decomposition	18
Temperature.....	18
Moisture	18
Individual variation.....	19
Cultural Factors	20
Animal activity.....	21
Estimating the post-mortem interval	21
Factors influencing time since death estimations.....	22
Accumulated degree days (ADD)	23
Cumulative degree hours (CDH)	24
Accumulated degree hours (ADH).....	25
Stage-based scoring systems.....	26
Animal models in decomposition research.....	27
Implications for forensic casework	29
Chapter III. Insects and the Postmortem Interval.....	32
Species	32
Seasonality	33
Geography.....	34
Growth and development.....	36
Temperature	37

Toxicology	39
Predatory species	40
Insects and decomposition	41
Collection and preservation in forensic contexts	43
Animal models in entomology studies	45
Chapter IV. Chaos Theory, Non-linear Systems Theory and Complexity Science.....	48
Chapter V. Materials and Methods	57
Sample composition	57
Human sample	57
Pig sample	58
Placement procedures	58
Data collection procedures.....	62
Photographs	63
Decomposition Scoring	63
Insect collection	65
Data analysis	66
Insect taxonomic identification	66
Insect activity patterns	66
Scavenging	67
Statistical analyses.....	67
Hierarchical linear modeling (HLM)	67
Time series (dynamic linear regression)	70
Chapter VI. Insect Results.....	74
Insect species identification	74
Insect activity patterns	75
Trial 1 spring.....	76
Trial 2 summer	86
Summary	91
Chapter VII. Scavenging Results.....	92
Trial 1 spring.....	94
.....	96
.....	96

Trial 2 summer	99
Trial 3 winter.....	105
Chapter VIII. Statistical and Numerical Results	114
Trial 1 spring.....	114
Scoring	114
Temperature.....	114
Trial 2 summer	114
Scoring	114
Temperature.....	116
Trial 3 Winter.....	116
Scoring	116
Temperature.....	118
Statistical analyses.....	120
Hierarchical linear modeling.....	120
Time series- dynamic linear regression	124
Chapter IX. Discussion	139
TBS results.....	139
Insect results.....	140
Scavenging results.....	140
Model results.....	142
Pig versus human	145
Sample size	146
Megyesi system.....	146
Theory.....	147
Hypotheses.....	148
Future directions of research.....	151
Conclusions.....	154
Works Cited.....	155
Appendices	179
Appendix A: TBS data	180
Appendix B: SAS code (SAS version 9.4) for HLM and Time Series Models.....	186
HLM for all trials.....	186

Dynamic linear regression models.....	191
Appendix C: Full reports for dynamic linear regression models.....	201
Trial 1.....	201
Trial 2.....	207
Trial 3.....	213
Vita.....	221

LIST OF TABLES

Table 1: Demographic information of all human and pig subjects.....	59
Table 2: Placement order for each trial. H=human, P=pig, R=.....	61
Table 3: Scoring categories and points for each body segment. From Megyesi et al., 2005.....	64
Table 4: Adult flies identified from Trials 1 and 2.....	75
Table 5: Insect activity patterns based on dates and anatomical locations for all subjects by trial.	76
Table 6: Scavenger type and minimum number of scavenging events by trial.....	93
Table 7: Body segment locations and counts of anatomical features scavenged by trial. Note that no pigs were scavenged during Trials 1 and 2.....	94
Table 8: Individual TBS examples from all three trials showing the variation between pigs and humans.	119
Table 9: p-values for fixed effects from the Hierarchical Linear Modeling of Trial 1 Spring. ..	122
Table 10: Estimates from the Hierarchical linear modeling for Body Segments in Trial 1 Spring subjects.	122
Table 11: p-values for Hierarchical Linear Modeling for Trial 2 Summer.....	123
Table 12: Estimates determined from the Hierarchical Linear Modeling for Trial 2 Summer...	123
Table 13: p-values for fixed effects from Hierarchical Linear Modeling of Trial 3 Winter.....	124
Table 14: Estimates of segment scores for Trial 3 Winter.....	124
Table 15: Autocorrelation check of residuals for pig model in Trial 1 Spring.	128
Table 16: Goodness of fit model assessment from pig model for Trial 1 Spring.....	129
Table 17: Models for pigs and humans for each trial.	133
Table 18: Model fit statistics for all models for all three Trials.	134

LIST OF FIGURES

Figure 1: Life cycle of a blowfly (https://www.flickr.com/photos/brettlider/72767638/).....	37
Figure 2: Trial 1 Spring area prior to clearing.....	60
Figure 3: Placement area with mesh.....	62
Figure 4: Trial 1 Spring, 114-13R with fly activity on face. Day 7.....	77
Figure 5: Trial 1 Spring, 116-13R with larval activity in the mouth. Day 12.....	78
Figure 6: Trial 1 Spring, 111-13R with egg masses on chin. Day 21.....	78
Figure 7: Trial 1 Spring, 112-13R (human subject) with larval activity in the right foot in an area opened by raccoon scavenging. Day 35.....	80
Figure 8: Trial 1 Spring, 113-13R with larval activity moving from face to neck and chest. Day 35.....	80
Figure 9: Trial 1 Spring, 107-13 R with larval activity on exterior near mouth and along ground-body interface (see arrow). Day 35.....	81
Figure 10: Trial 1 Spring, 107-13R with larvae on the exterior hind leg. Day 35.	81
Figure 11: Trial 1 Spring, 108-13R with fly activity on exterior head. Day 35.....	82
Figure 12: Trial 1 Spring, 108-13R with larval activity on hind leg. Day 35.....	82
Figure 13: Trial 1 Spring, 110-13R with larval activity in mouth and eye. Day 35.....	83
Figure 14: Trial 1 Spring, 114-13R with larval activity in axilla and underneath body (see arrows). Day 35.	83
Figure 15: Trial 1 Spring, human 112-13 R with larval activity in opening in leg. Day 35.....	84
Figure 16: Trial 1 Spring, 112-13R with larval activity in facial orifices. Day 35.	84
Figure 17: Trial 1 Spring, human 114-13R with larval activity under the epidermal layer of skin on the right leg (see arrow). Day 38	85
Figure 18: Trial 1 Spring, 107-13R with continued larval activity at the ground-body interface. Day 38.....	85
Figure 19: Trial 1 Spring, 112-13R with larval activity protruding out of the facial orifices. Day 38.....	86
Figure 20: Trial 2 Summer, Fly eggs on snout of 122-13R. Day 0.	87
Figure 21: Trial 2 Summer, 119-13R with fly activity and egg masses in nostril. Day 1.	88
Figure 22: Trial 2 Summer, 118-13R with larval activity protruding from nostril onto upper lip. Day 2.....	88
Figure 23: Trial 2 Summer, 123-13R with larval activity on snout. Day 3.	89
Figure 24: Trial 2 Summer, 123-13R with maggot masses from head and rear joining to encompass entire body. Day 5. Note the dramatic change from Figure 20, which was only two days prior.....	90
Figure 25: Trial 2 Summer, 118-13R with larval activity in eyes and right arm at scavenging opening. Day 4.....	90
Figure 26: Trial 2 Summer, Close up of 118-13R larval activity in opening in right arm made by raccoon scavengers. Day 4. Note that the larvae are contained within the scavenging site and not joining up with other masses as observed on the pigs.	91
Figure 27: Raccoon scavenging the left arm of human 112-13R.	95
Figure 28: Opossum scavenging left arm of human 112-13R after raccoon has created opening.	95

Figure 29: Raccoon returning to original scavenging site of human 112-13R.	96
Figure 30: Raccoon scavenging left leg of human 112-13R.	96
Figure 31: Raccoon expanding on scavenging site of left leg of human 112-13R.	96
Figure 32: Opossum returning to original scavenging site on left arm of human 112-13R; possibly consuming fly larvae.	97
Figure 33: Raccoon removing muscle tissue from the left leg of human 112-13R.	97
Figure 34: Opossum eating larvae from near human 112-13R.	98
Figure 35: Raccoon opening foot of human 112-13R.	98
Figure 36: Opossum accessing same scavenging site as raccoon on human 112-13R.	99
Figure 37: Multiple raccoons (n=3) examining the placement area of Trial 2 Summer.	100
Figure 38: Opossum in the placement area of Trial 2 Summer.	100
Figure 39: Raccoon approaching human 119-13R.	101
Figure 40: Opossum near human 119-13R.	101
Figure 41: Group of raccoons (n=4) scavenging human 119-13R.	102
Figure 42: Raccoon scratching left shoulder of human 117-13R.	102
Figure 43: Raccoon removing tissue on left shoulder of human 117-13R.	103
Figure 44: Maggot mass in left shoulder of human 117-13R where raccoon scavenging occurred.	103
Figure 45: Raccoon scavenging right shoulder of human 117-13R after the left shoulder was scavenged earlier. This demonstrates the proclivity of the raccoons to preferentially scavenge certain individuals.	104
Figure 46: Opossum using raccoon scavenging site on right shoulder of human 117-13R.	104
Figure 47: Multiple raccoons scavenging right side of human 117-13R.	105
Figure 48: Skunk on top of human 143-13R. Tissue damage to 143-13R observed the following day suggests that the skunk fed on the remains.	106
Figure 49: Raccoon scavenging pig 134-13R.	106
Figure 50: Opossum scavenging pig 134-13.	107
Figure 51: Skunk scavenging pig 134-13R. The skunk is at the back of the pig, and only the tail of the skunk is visible. See arrow.	107
Figure 52: Raccoon returning to scavenge pig 134-13R despite snow.	108
Figure 53: Skunk returning to pig 134-13R during snow.	108
Figure 54: Juvenile raccoon playing with data logger.	109
Figure 55: Multiple raccoons (n=2) scavenging human 142-13R simultaneously.	109
Figure 56: Raccoon removing muscle tissue from human 142-13R.	110
Figure 57: Opossum feeding from scavenging site made by raccoons on human 142-13R.	110
Figure 58: Raccoon near human 144-13R. Note the scavenging damage to the face and neck.	111
Figure 59: Raccoon actively scavenging face and neck of human 144-13R.	111
Figure 60: Opossum feeding from raccoon scavenging site on human 144-13R.	112
Figure 61: Raccoon returning to human 144-13R to remove muscle tissue from the left arm.	112
Figure 62: Average Daily TBS for Humans and Pigs in Trial 1 Spring.	115
Figure 63: Average daily temperature trends in Trial 1 Spring.	115
Figure 64: Average human daily TBS and average pig daily TBS.	116
Figure 65: Average daily temperature trends in Trial 2 Summer.	117

Figure 66: Average human daily TBS and average pig daily TBS.	117
Figure 67: Average daily temperature trends in Trial 3 Winter.	118
Figure 68: ACF plot for pig model, Trial 1 Spring showing lags where a Moving Average term is needed. Note how the series decreases quickly, showing a strong autocorrelation relationship.	126
Figure 69: PACF plot for pig model, Trial 1 Spring showing the Autocorrelation term needed. Note how there is a strong spike at the first column, and then the columns cluster close to 0... ..	126
Figure 70: Predicted versus actual TBS values for pig data in Trial 1 Spring, with 95% C.I. values represented by the solid line. A 95% confidence interval for the predicted data is depicted in the shaded area. The dashed line towards the right of the graph indicates where the actual values ended and the predicted values began.....	129
Figure 71: Actual human TBS values from Trial 1 Spring compared to the forecasted fit line developed from the pig model.	131
Figure 72: Actual human TBS values plotted against forecasted pig TBS to check for a linear relationship for Trial 1 Spring.	132
Figure 73: Actual human TBS values in circles compared to predicted TBS values in the line. 95% confidence interval for predictions in gray. Note the difference in pattern of the human values as compared to the pig values from Figure 70.....	133
Figure 74: Actual human TBS values in circles compared to the forecasted fit line for Trial 2 Summer. Confidence interval is in gray.....	137
Figure 75: Actual pig values in circles compared to the forecasted fit line. The 95% C.I. is in gray. Data is for Trial 2 Summer.	137
Figure 76: Actual human values in circles compared to the forecasted fit line. The 95% C.I. is in gray. Data is for Trial 3 Winter.	138
Figure 77: Actual pig values in circles compared to the forecasted fit line. The 95% C.I. is in gray. Data is for Trial 3 Winter.	138

Chapter I. Introduction

Estimation of postmortem interval (PMI) is an important forensic anthropological tool for narrowing down the window of time in which an individual could have died. It aids law enforcement in the identification of unknown individuals and in evaluating the alibis of potential suspects. Actualistic studies (experimental models) in decomposition increase the accuracy and precision of PMI estimations. However, human remains are not always available for use in such studies due to legal prohibitions or community objections, and domestic pigs have become the primary substitute for humans in decomposition research (Cablík et al., 2012, Grassberger and Frank, 2004, Anderson and VanLaerhoven, 1996). The problem is it is not well understood how domestic pig decomposition patterns differ from human decomposition patterns. This difference between species could impact the level of inaccuracy regarding PMI estimations when working with data generated by pig models.

In 1965, Payne published the article “A Summer Carrion Study of the Baby Pig *Sus scrofa Linnaeus*” in the journal Ecology. The stated primary goal of the article was to investigate the role of arthropod activity on the rate of decomposition. In order to accomplish this, several of the pigs were protected from insect activity, while others were left in areas that were open to insect colonization. Payne concluded that arthropod activity was a significant contributor to the decomposition process, and that a definite ecological succession occurred for various arthropod species. These two conclusions have been cited and reaffirmed by multiple studies since 1965 (e.g. Goff, 1993, Grassberger and Frank, 2004, and Spicka et al., 2011).

Payne’s article is not best known for the stated goals or conclusions of his research, however. Instead, it is a brief discussion in the materials and methods section that has led to this work being cited over 700 times. Payne describes a series of initial carrion tests that he ran to

decide what animal model would work best for his project. He tried frogs, toads, two species of mice, shrews, rats, and chipmunks before deciding that those animals were all too small to be able to easily and accurately observe arthropod activity and decomposition (Payne, 1965). Larger carrion were also tested, including cats, dogs, rabbits, squirrels, chickens, other birds, and pigs. Dogs and cats proved to be too difficult to obtain in uniform size, the feathers of the chickens and birds obscured the insect activity, and the squirrels and the rabbits (collected from roadkill) were too damaged and had an unknown time since death (Payne, 1965). Domestic pigs (*Sus scrofa*) were determined to be the best option because they could be easily obtained in large number and of relatively equal sizes, and they had no feathers.

Payne's conclusion that domestic pigs were the best animal model of the species available was not meant to be the primary message to the academic community. Yet this article has been repeatedly cited as the primary source stating that pigs are the best animal proxy for human remains in entomology and decomposition studies (e.g. Early and Goff, 1986, Hewadikaram and Goff, 1991, Anderson and VanLaerhoven, 1996, Campobasso et al., 2001, Wolff et al., 2001, Centeno et al., 2002, DeVault et al., 2003, Amendt et al., 2004, Grassberger and Frank, 2004, Carter et al., 2007).

Spiraling further from there, multiple studies have further expanded the claim to state that domestic pigs are such a strong proxy for human remains that data based on pig studies can be directly applied to human forensic contexts without any further investigation. Many of these studies (e.g. Spicka et al., 2011) cite those previously listed articles which cite Payne (1965) for their justification in the use of pig remains. In sum, a statement that domestic pigs were a more suitable research subject than frogs, chickens, or roadkill squirrels has become distorted into the

statement that pigs can substitute for human remains in entomology, decomposition, and taphonomic research.

A real research need exists for a suitable non-human animal proxy for human remains in taphonomic studies. A research facility opened at the University of Tennessee in 1981 that was specifically dedicated to studying decomposition patterns using human remains (Mann et al., 1990). Currently there are only eight research facilities in the United States that are able to use human remains for decomposition and taphonomic research. All other facilities must rely on a non-human proxy. While some studies (e.g. Schoenly et al., 2007) have compared pigs and humans directly, the focus has only been on one variable at a time.

Examining one isolated variable at a time presents a theoretical problem in the approach of decomposition research. Many studies endeavor to control all but one variable so it can be determined if and how that particular variable affects the rate of decomposition. Decomposition is a complex and complicated process, so altering one variable means that that variable is going to interact with all of the other variables in often unpredictable ways. Thus comparing pigs and humans on one variable at a time may show that there are similarities on that one particular aspect, but does not really address if their overall patterns and rates of decomposition are actually still similar between pigs and humans. For example, there has been one study that has specifically asked if different insect species are attracted to different carrion types (Schoenly et al., 2007). This is important because it is very well established that insect activity is significant in driving the rate of decomposition. Schoenly and colleagues demonstrated that there does not seem to be a significant difference in terms of the type of species of insect that is attracted to either pig or human remains, yet no other questions were asked. Species or type of insect is not the only component of insect activity. The study did not address aspects of timing- if flies would

oviposit on pigs sooner than humans or vice versa, or asking about how long the insect activity would last on each species. Decomposition has been broken down to asking about only one very specific variable, and the conclusion was reached that because insect species type appears to be the same then any research done on pigs can be directly applied onto human situations like forensic cases without any further investigation. Many would suggest that this is likely not the case, and pigs are not perfect replicates of humans in terms of decomposition.

This dissertation argues that much of the variability in decomposition is circumvented by eliminating the impacts of interaction effects between different variables. To date, there has never been a large scale comparison between domestic pigs and human remains examining multiple variables simultaneously to see if decomposition patterns vary to such an extent that pigs cannot be used as a direct substitute for humans. And that is truly the question that must be asked. Not just if there are some similarities, but if research conducted using pigs produces information that can be directly applied to a human context.

In order to test if pigs can be used as a direct substitute for humans, several considerations should be examined. First, it would be beneficial to re-frame how researchers think about decomposition studies. Taphonomists need to move from a Newtonian or reductionist theoretical framework where the attempt is made to isolate a single variable to see how that one aspect is going to drive the variation, and instead study decomposition as an overall complicated process of interacting variables and a process that is very sensitive to initial conditions. Sensitivity to initial conditions means that if variable states are different at the start of the process, in regards to this dissertation research the start is the time of death, the entire process is going to be impacted. For example, humans may vary extensively in terms of health states, medications, and diet. All of those factors can affect the gut flora that drive much of the

microbial aspects of decomposition. In addition, there are the interactions of the variables that can also alter the rate and progression of decomposition. It is not always possible to see or test all of those variables. For this dissertation, the focus will be on several key aspects simultaneously to assess if pigs can be used as a substitute for human remains.

Decomposition progression will be examined by morphological indicators, using the Total Body Scoring (TBS) system developed by Megyesi and colleagues in 2005. While this scoring system was designed for photographs and not designed for in-person observation, it is one of the most widely used in taphonomic research. TBS is also one of the few stage-based scoring methods that applies consistent terminology superior to previous methods that assess only broad categories of decomposition.

Insect activity is another critical variable impacting the rate of decomposition progression. As measured by location of larval mass, by duration of larval and insect presence, it is anticipated that insect activity will vary between pigs and humans. Variation in insect patterns may be reflective of the biological differences between pigs and humans as well as the anatomical differences. For example larval mass location could be due in part to positioning. Pigs will be placed on their side, humans are going to be laid on their backs. Therefore, larval mass location and the overall distribution of larval activity could vary by anatomical differences and how remains lie on the ground. The distribution of larval masses could impact which region(s) of the body show earliest bone exposure, which in turn alters the TBS. In addition, there is a different distribution of weight between the pigs and the humans. Humans may have less body fat than the pigs, and the bulk of the mass in the pigs is mostly centered in the trunk, which is not necessarily true for the humans. Given that the TBS method analyzes the trunk

separately from the limbs, varying amounts of body mass by region could directly affect segment scores, if not overall TBS.

Other animals that are attracted by the opportunity to feed on the remains can also increase the rate of decomposition progression. One of the scavengers that has been observed most frequently at the Anthropology Research Facility (ARF) is raccoons (*Procyon lotor*). The raccoons are specifically consuming muscle tissue (Synstelein, 2015). Raccoons typically begin scavenging at the limbs (Smith, 2015). Anatomical differences between pigs and humans include that humans have much larger muscle masses in their limbs compared to pigs. If the raccoons' typical scavenger behavior follows what has been previously observed, then raccoons would be more likely to scavenge the humans because there is greater muscle yield from those limbs. In addition there is a skin thickness difference. The hide of the pigs is tougher than that of the humans, meaning that the humans may present an easier scavenging target than pigs.

To help fill in the knowledge gap of how human and pig decomposition patterns vary, this dissertation examines the validity of using domestic pigs (*Sus scrofa*) as a substitute for human remains in decomposition research. Although this is not the first study to directly compare pig and human remains in decomposition contexts (Schoenly et al., 2007) it is the first to compare the decomposition patterns with respect to multiple variables and across three seasons. Comparing both species side by side for three seasons and using morphological indicators of decomposition, insect activity patterns and scavenging patterns to differentiate decomposition between pigs and humans is critical as this project therefore represents the largest and most holistic direct comparison of pig and human decomposition to date.

It is well established that many intrinsic and extrinsic factors influence the rate of decomposition and therefore complicate the estimation of time since death (e.g., Wilson and

Dautartas, 2017, Marks et al., 2009, Gill-King, 1997, Mann et al., 1990, Galloway et al., 1989).

In an effort to better understand these factors and increase the accuracy and precision of postmortem interval estimations, studies have been conducted on morphological indicators of soft tissue decomposition (Shirley et al., 2011), entomological activity (Farrell et al., 2015), microbial activity (Hyde et al., 2013) and the impact of scavengers (Beck et al., 2015), to name only a few. Some of these studies utilized human remains; others used porcine models. Whether based on human or animal subjects, the information gleaned from this research is intended to be used in forensic contexts involving human remains with an unknown post-mortem interval. This application of data gathered from porcine studies to human casework is what makes the current research question significant. The key question to address is whether or not patterns of decomposition are similar between domestic pigs and humans, and if the patterns of decomposition are in fact similar, then do they mirror each other enough that data taken from pig models can be used to predict human values in forensic cases.

Adequately addressing the question of whether pigs are a suitable substitute for humans in decomposition research requires an expansion in the currently existing theoretical framework. Forensic anthropology has been criticized for lacking a strong, in-depth theoretical base (Boyd and Boyd, 2011, Komar and Buikstra, 2008). Taphonomic researchers, in particular, have focused on moving taphonomy beyond case studies and anecdotal evidence to research designs with statistical and theoretical strength (Dirkmaat et al., 2008). Non-linear systems theory provides the theoretical basis for this dissertation. This approach is appropriate as non-linear systems theory centers on evaluating the behavior of complicated and complex phenomena in order to gain a more accurate and nuanced understanding of the process as a whole. Decomposition has frequently been studied with a more Newtonian focus; this means the focus

has been on isolating specific variables of factors such as clothing, sun versus shade, and coverings (e.g. Cahoon, 1992, Miller, 2002, Srnka, 2003, Dautartas, 2009). While these studies have contributed to an increased understanding of the factors that can impact the rates of decomposition, these reductionist studies have not fully addressed questions as to why decomposition rates vary between individuals in the same and different contexts. This may be because the decomposition process is more than the sum of its individual parts. Thus, treating decomposition instead as an integrated system with many factors and interactions is more likely to produce a thorough understanding that will enable more accurate and precise estimation methods. Non-linear systems theory will assist in refocusing the study of decomposition from analyzing how individual factors impact the rate of the process to how multiple variables interact to produce the observable patterns that provide the data for estimation of PMI.

This emphasis on the process as a whole is particularly important for evaluating if pigs can be used as a substitute for humans in actualistic decomposition studies. The studies that have directly compared the two species only focused on one aspect at a time. For example, one study (Schoenly et al., 2007) examined whether or not the same species of forensically significant insects would be attracted to both pig and human remains that were placed in the same location. This study did not address any other aspect of insect behavior such as timing of colonization or development rates, and it did not seek to address if the overall patterns of decomposition were comparable between the two species. Another study (Parkinson, 2009) investigated the microbial communities associated with decomposition and found that similar microbes were present in both pigs and humans. Again, this study did not address any other characteristic of microbial activity, nor did it assess if the two species decomposed at the same rate. These two studies both concluded that pigs could be a useful substitute for studying decomposition patterns and that the

information derived from porcine models could be applied to forensic contexts involving human remains.

The theoretical aim of the current study is to move beyond focusing on a single isolated variable and work with decomposition as a process. This will be done by simultaneously evaluating progression of decomposition, as reflected by morphological characteristics, insect activity patterns and scavenging activity. Examining decomposition as a complex process will provide a more thorough understanding of if and how domestic pigs and humans decompose in a similar manner. It is anticipated that although pigs and humans share some decomposition characteristics, such as attraction of similar insect species, not all of the aspects of decomposition will be the same between the two species. It is further suspected that the complicated relationships between decomposition variables will then lead the overall rates and patterns of decomposition between pigs and humans to vary to such a degree that one species cannot serve as a substitute for the other. In order to test these ideas, the following goals and hypotheses will be addressed.

Research goals and hypotheses

The purpose of this project is to determine if the patterns and rates of decomposition between humans and domestic pigs vary to the extent that models developed from pig data are significantly different than the actual human decomposition data. This is critical to addressing the problem of whether or not domestic pigs can be used as a direct substitute for human remains when developing PMI estimation methods. The following hypotheses were used to address this question. The first hypothesis reflects the overall goal of this research- to investigate overall patterns of decomposition between the two species. The subsequent hypotheses identify specific areas that were used to describe the similarities or differences in the observed patterns. In addition to the visual observations used to address each hypothesis, statistical methods that have

infrequently been applied to taphonomic questions were used to quantify pattern variation. This project used hierarchical linear modeling to evaluate the similarity of decomposition patterns between pigs and humans, and used time series statistics to investigate if models developed from pig data could accurately predict actual human PMI values.

Hypotheses

1. *Human subjects will vary much more within species than will pig subjects.* Like most research projects using porcine subjects, the pigs for this project all came from the same farm, and were ostensibly fed the same diet and lived in the same microenvironment. Conversely, the human donors came from various locations in the United States, and had much more diversity in diet, activity patterns, and individual health states, which impact their patterns and rates of decomposition. The reason for this difference may be multifaceted and is unlikely to be fully explained by this research, but the variation amongst humans may minimally reflect biochemical and microbial diversity.
2. *Assignment of TBS will more accurately reflect decomposition changes in human subjects than porcine subjects.* The total body scoring (TBS) system that was used in this project was developed by examining photographs of human remains and is designed to be used on humans. Although morphological decomposition changes, such as color change and skin slippage, could be observed on the pig remains, the changes are unlikely to have the same patterns as described in the TBS categories.
3. *Insect activity, as measured by location of larval masses and length of presence of insects, will vary between pigs and humans.* Multiple studies document the importance of insect activity in driving the rate of decomposition patterns (Simmons et al., 2010). As

the humans and pigs will be positioned differently (pigs on their sides, humans on their backs) insects will have different access to sites for oviposition, and this will lead to differences in location of larval masses. These masses may have a noticeable impact on the body segment and total body scores as the larvae consume tissue in different locations on the humans and pigs. Overall body size and weight distribution may also lead to various lengths of time for insect activity overall.

4. *Insect activity, as measured by species type, will not vary significantly between pigs and humans.* The subjects were placed at the same time and in the same microenvironment, with no obstruction to insect activity. A previous study has demonstrated that similar fly and beetle species will colonize on human and porcine remains (Schoenly et al., 2007).

5. *Human subjects will be more likely to be scavenged by raccoons than will the pigs.*

Raccoons at the ARF have been documented to scavenge muscle tissue from the limbs of human donors. Both the upper and lower limbs of the humans have much larger muscles than the front or rear limbs of the pigs, which could lead the raccoons to preferentially scavenge the humans. The hide of the pigs is also considerably tougher than human skin, making the pig muscle more difficult for the raccoons to access. This potential difference in scavenging activity could significantly impact the PMI estimates generated from both species.

Significance

This project systematically compared the decomposition of human and pig remains over three seasons. With a total sample size of thirty subjects, it is one of the larger decomposition studies to be conducted at the Anthropology Research Facility. In addition to employing and

evaluating a widely used scoring system to assess gross morphological changes during decomposition, this project also examines animal and insect activity. The analytical techniques in this study are progressive in the application of hierarchical linear modeling and time series statistics. Neither approach has been frequently applied to decomposition studies of human or animal remains.

This study addresses a primary gap in the forensic anthropology literature. The question exists whether data gleaned from pig decomposition studies can be used to construct models that will be useful predictors of human patterns. This is critical information as pigs are currently held as the best proxy for humans. Addressing if pigs are similar enough to be a substitute for humans in taphonomic research also addresses the need to determine what standards should be set for a “suitable” proxy. Post-mortem interval estimation is one component of a forensic anthropology report that could be challenged in court, and care must be taken to ensure the research produced will meet accuracy requirements. The results of this study could help to determine best practices both for currently operating decomposition facilities and also for any future facilities.

Organization of dissertation

Chapters two and three discuss the basics of decomposition and insect activity, respectively. The fourth chapter provides a detailed explanation of non-linear systems theory, which informed the perspectives of this research. Materials used in the study and methods of data collection and analysis are presented in Chapter 5, followed by individual chapters for insect results, scavenging results, and the results of the statistical analyses. These are discussed in detail in Chapter 9, which also examines future directions of research and conclusions that can be drawn from this study. Only a small subset of data collected during this project is presented in the text of this dissertation.

Chapter II. Soft Tissue Decomposition

The question of whether domestic pigs can be used as a substitute for humans in decomposition studies centers around whether the patterns and rates of decomposition of the two species are similar. In order to evaluate if the two species decompose in similar ways within the same environments, it is first necessary to identify and define the characteristics that will be used to mark the progression of decomposition. As there is also different terminology suggested for decomposition stages (e.g. Janaway, 1996, Megyesi et al., 2005, Marks et al., 2009) it is also critical to establish the language that will be used to discuss decomposition in this project. The stages discussed here are a combination of the stages suggested by Janaway (1996) and Marks and colleagues (2009).

Beyond determining common language, this review also defines several key processes that lead to the macroscopic changes that will be assessed. An understanding of these mechanisms is needed to interpret the differences and similarities observed between the decomposition patterns of the two species. During soft tissue decomposition, multiple variables act and interact simultaneously to produce a specific pattern, and seemingly subtle differences between starting conditions or small deviations during the process can lead to strikingly distinct outcomes.

After a discussion of the biochemical processes of soft tissue decomposition, this chapter will provide an overview of factors that can alter the rate of decomposition progression. Practical aspects of decomposition studies including their application to postmortem interval estimation and the use of animal models in decomposition research is also included. Insect activity is a key variable that requires a more thorough review and will be discussed in the next chapter.

Fresh stage

Autolysis

Autolysis is the name given to the earliest biochemical process in decomposition and is the process of cell death following somatic death (Marks et al., 2009). The cessation of circulatory activity and the subsequent loss of adenosine triphosphate (ATP) causes rupture of the cell wall and release of enzymes from the cell wall into the extracellular matrix (Spitz and Fischer, 1980). This process then leads to a drop in the pH of the cytoplasm. Enzymes within the cytoplasm then become active and further deteriorate the cellular material. Simultaneously, aerobic bacterial activity uses the available oxygen released from the body tissues. This depletion of oxygen then provides an anaerobic environment hospitable to the bacteria responsible for putrefaction (Dent et al., 2004). Hydrolytic splitting of fats, proteins and carbohydrates happens concurrently with other autolytic changes (Janssen, 1984). Oxidative reactions may also occur during this time, but are dependent upon sufficient oxygen availability (Dent et al., 2004).

Externally, color change is evident in the skin, which may become paler, and skin slippage is often observable as the cellular junction between the epidermis and the dermis breaks down (Marks et al., 2009). Discoloration, frequently green or grey, due to bacterial activity is often observable in the abdominal region. Autolysis also prompts three morphologic changes frequently analyzed by pathologists: rigor, algor, and livor mortis.

Rigor mortis

Rigor mortis refers to the process of muscle stiffening that results from a buildup of lactic acid in the tissues following death (Janaway, 1996). The muscles will stiffen, and eventually all of the muscle tissue in the body will become fixed and immobile (Spitz and Fischer, 1980). This process begins roughly within 1 to 2 hours after death, peaks at twelve hours postmortem, begins to recede within the next twelve hours, and eventually dissipates (Marks et al., 2009). This

process takes time to complete because cell death and the buildup of waste products do not happen instantaneously. Once the process has completely subsided, the body will be limp and flexible.

Livor mortis

Another process that may aid in estimating the postmortem interval is livor mortis, or hypostasis (Kaatsch et al., 1994). When circulatory activity ceases, blood responds to gravity and settles in the lowest points of the body, creating visible red areas on the skin (Baden and Hennessee, 1989). This process, although affected by other variables, generally begins within an hour postmortem and takes approximately eight to twelve hours to complete (Coe 1993, DiMiao and DiMiao, 2001, Marks et al., 2009). In addition, if a body is moved after this time period, lividity will be fixed and “stains” will be visible at the original site of contact. The pools of blood will not travel if the body is moved, and therefore can be useful in determining not only the postmortem interval but primary or secondary placement as well (Perper, 1993).

Algor mortis

Algor mortis refers to the lowering of the body temperature postmortem. Historically, it was thought that body temperature dropped two degrees within the first twelve hours after death, and then continues to decrease at a rate of about one degree per hour (Perper, 1993). However, it has been established that the initial temperature drop is slow, and then the rate of cooling increases (Henssge et al., 1995). In addition, the body temperature is also affected by ambient temperature and bacterial activity, decreasing its effectiveness as a time since death indicator.

Each of these processes has been used to estimate a time since death early in the decomposition sequence, although their accuracy and reliability remains questionable. Any

utility offered by these techniques will typically cease at thirty-six hours postmortem, creating a need to develop a timeline for the processes later in the decomposition sequence.

Putrefaction

Fueled by endogenous bacteria proliferating in the remains, putrefaction is a destructive biochemical pathway of organism degeneration (Marks et al., 2009). As the oxygen within the body decreases, this creates a more suitable anaerobic environment for the destructive bacteria responsible for putrefaction activity (Macchiarelli and Feola, 1995). Most of the bacteria inside the body are concentrated within the cecum, and therefore most of the external signs of putrefaction are first visible in the lower abdominal area (Love and Marks, 2003). Bacteria do not remain in the intestines; they spread to the lungs and the rest of the body, although to a lesser degree. Bacteria also systematically invade the circulatory system as they are capable of colonizing fluids easily (Marks et al., 2009). Macroscopically, discoloration in the blood vessels is visible due to this bacterial activity and its role in the degradation of hemoglobin and the conversion of heme into bile pigments (Wilson-Taylor, 2012). Bilirubin appears as a red pigment in the skin, biliverdin is green, and urobilin appears brown (Gill-King, 1997).

By-products of this anaerobic respiration of the intrinsic bacteria include large-scale production of hydrogen and other gases that cause observable bloating of the abdominal cavity (Vass, 2001). In addition, the discoloration that begins in the abdomen spreads to other areas of the body as the bacteria travel throughout the tissue. Pressure from the gaseous buildup inflates the cadaver and aids in the expulsion of fluid (sometimes referred to as “purge”) (Janaway et al., 2009).

Active decomposition

Once most of the gases have been expelled and the tissue continues to break down, bloating ceases. Prior to the complete cessation of bloating, initial skeletalization may begin (Love and Marks, 2003). Skin cracks and eventually disintegrates along with other soft tissues (Galloway et al., 1989). The internal tissue becomes increasingly exposed to the environment, which allows for oxygen to enter in. This, then, increases the aerobic bacterial activity, which accelerates tissue decomposition (Rodriguez and Bass, 1983). Any remaining head hair sloughs off from the body and forms a “hair mat,” a mass of matted hair which collects beneath the head. Bodily fluids leak out of the body, which allows for the exposure of bone, and the remains may begin drying out.

In warm, moist, alkaline conditions, lipids that remain after the anaerobic fermentation of putrefaction may undergo hydrolysis, or hydrogenation, to form adipocere. Adipocere can present as a soft, paste-like substance or it can have a hard texture depending on the environmental and chemical conditions during formation. Formation of adipocere is highly environmentally dependent; conditions such as high humidity or a burial environment promote adipocere development (Forbes et al., 2005).

Mummification of soft tissue may also occur, but this is again environmentally dependent. Connective tissues such as the ligaments and tendons as well as overlying skin are the tissues that mummify most frequently (Wilson-Taylor, 2012).

Once bloating has completely ceased and bone exposure has initialized, the body can be considered to be partially skeletonized. Soft tissue will continue to deteriorate, and eventually disappear completely (Marks et al., 2009).

Factors affecting the rates of decomposition

A host of factors can affect each stage of the decomposition process, either accelerating the process or slowing it down, depending on the specific agent at work. Some of the most frequently observed variables are temperature, moisture, insect activity, and sun or shade exposure (Tomlinson, 2003, Srnka, 2003). Whether the remains are left on the surface or have been buried or submerged also has a significant impact on the rate of decay (De Donno et al., 2014). Typically, several or all of these influences affect the decomposition process, and the effects are seen in multiple stages. Patterns of decomposition are so variable and complicated because of these interaction effects.

Temperature

Temperature has the greatest impact on the rate of decomposition (Gill-King, 1997). The general trend observed is that warmer conditions will promote decay, and colder climates will delay the process (Mann et al., 1990, Megyesi et al., 2005, Simmons et al., 2010). Warmer environments are more favorable for insect activity, which accelerates decomposition (Haskell et al., 1997). Temperatures between 60 and 95 degrees Fahrenheit are correlated with peak activity of colonic bacteria (Micozzi, 1997). In temperatures below 55 degrees F and above 100 degrees F, bacterial activity decreases dramatically (Marks et al., 2009). Surrounding plant matter can also have an effect on decomposition by influencing temperature. Mant (1987) found in his examination of World War II burials that straw and pine needles covering decomposing matter retained heat produced by the decomposition process and generated heat through their own breakdown, which increased the rate of decomposition.

Moisture

The amount of moisture surrounding the body also factors into the duration of decomposition. Typically, a moister environment fosters decomposition, and more arid climates

retard the process (Galloway et al., 1989). Well-drained, dry soil has also been shown to be conducive to mummification (Mant, 1987). The combination of heat and aridity can be particularly likely to lead to mummification of remains. This combination is a strong example of how factors often interact to affect the rate of decomposition. Aturaliya and Lukasewyz (1999) examined the importance of moisture content to the rate of decomposition by using rat carcasses in a taphonomic study. Their research noted that the material or environment that was in direct contact with the skin of the decomposing body made the most significant impact in moisture loss or retention. Materials such as cotton that absorb moisture and then allow for evaporation accelerate water loss and lead to faster desiccation of tissue or mummification (Dautartas, 2009). Materials like plastic tarps that allowed water to collect on a body prevented mummification, regardless of whether the body was buried or placed on the surface (Aturaliya and Lukasewyz, 1999, Dautartas 2009). Rates of decomposition of bodies submerged in water are influenced by the water's temperature, depth, salinity, water chemistry, and aquatic life (Seet, 2005).

Individual variation

Decomposition can also be affected by physical conditions of the individual (Stuart, 2003). Leaner bodies tend to skeletonize more rapidly than individuals with extremely high body fat content (Mant, 1987). Body fat itself will not slow the decomposition process. This is partially due to the fact that an excessive amount of body fat can hinder dissipation of heat, and heat is an essential component of rapid decomposition (Zhou and Byard, 2011). In addition, body fat provides an ample amount of liquid needed for bacterial growth, which is active during several stages of decomposition. Thus, although bodies with a higher fat content will begin to decompose quickly, the overall process leading to skeletonization will require more time (Sutherland et al., 2013). An antemortem infection can also contribute to accelerated

putrefaction, as microbial agents are already active within the body prior to the start of decomposition (Zhou and Byard, 2011). Wounds on the body may also accelerate decomposition, primarily due to their influence on attracting insect activity. Insects typically approach natural orifices; wounds provide additional places for feeding and egg deposition (Mann et al., 1990).

Cultural Factors

Cultural factors refer to any variable that results from human action as opposed to naturally occurring environmental features. These can include clothing or wrapping the body, burying remains or placing them in a container. Alterations to the remains themselves, such as burning, dismemberment or attempted chemical destruction can also be considered cultural variables. Because cultural factors directly result from human behavior, they can be difficult to anticipate. While studies have been conducted on some of these variables, it is likely that there are others that have yet to be investigated.

The impact of cultural factors is not always straightforward. Studies on clothing have shown that depending on the material type and its interaction with environmental factors, clothing may either accelerate or slow down decomposition (Cahoon, 1992, Miller 2002). Burning of remains has also produced inconsistent effects on decomposition. Avila and Goff (1998) found that burning had no impact on either the rate of decomposition or insect succession in the post-burn period. In contrast, Gruenthal and colleagues (2012) found that body regions with significant charring decomposed at a faster rate, while areas with only light charring decomposed more slowly. Dismemberment decelerates decomposition, as individual body segments tend to break down more slowly than intact remains (Delabarde and Ludes, 2010).

Chemical alterations to remains can impact decomposition as well. Quicklime and hydrated lime have been shown to delay decomposition (Schotsman et al., 2012).

Animal activity

Non-insect scavengers can also affect decomposition rates. Canids and rodents can partake in dismemberment and disarticulation of a body during decomposition. Large carnivores such as wolves, dogs, or coyotes are usually primarily responsible for disarticulating limbs from the torso and for eating away at the face, neck, and abdominal areas (Haglund, 1997, Willey and Snyder, 1989). Dogs and coyotes are more frequently reported scavengers than wolves (Haglund, 1997). Rodents typically gnaw at the long bones (Haglund et al., 1989, Klippel and Synstelien, 2007). Both the carnivores and rodents also are known for scattering remains, which can lead to increased bone exposure and subsequent damage to the skeletal material (Haglund, 1997).

Procyonids (raccoons) have also been documented feeding on decomposing remains (Synstelien, 2015, Smith, 2015). Raccoons are highly opportunistic scavengers, and have been shown to be adaptable to urban environments (Smith, 2015). Unlike other scavengers, their seasonality is variable; depending on the climate of a particular year and the corresponding availability of food they may be highly active during the entire year. Therefore, if a food source is available year-round, raccoons may be active the entire year as well (Smith, 2015).

Avian scavengers, namely vultures, have also been documented feeding on remains (Reeves, 2009). Black and turkey vultures are the most frequently seen. These scavengers can consume enough tissue to completely skeletonize remains within 5 to 27 hours of feeding (Reeves, 2009, Spradley et al., 2012).

Estimating the post-mortem interval

Precise and accurate estimations of the postmortem interval are the goal of studying how various factors influence the rate of decomposition. Scientists attempt to take the information

garnered from anecdotal cases and actualistic studies and develop formulae or discrete patterns that can be applied in a wide variety of scenarios. For example, Vass et al. (2002) studied the chemical composition of decomposing remains in order to develop usable biomarkers for determining PMI. In order to develop a usable timeline, bodies were allowed to decompose at a research facility over a time period of four years, and tissue samples were collected to be analyzed for specific biomarkers, such as amino acids and neurotransmitters (Vass et al., 2002). This chemical signature was then correlated to time since death. Ideally, this information could then be applied to future cases, and PMI can be estimated based on the chemical composition of a tissue sample taken from a recovered body. Other methods for estimating PMI include tracing larval development of forensically significant fly species (Baque and Amendt, 2013), or creating a “clock” based on microbial activity (Metcalf et al., 2013). Each method relies on different techniques and information, and each method is subject to error ranges and biases. Research continues to refine techniques for improved performance.

Factors influencing time since death estimations

Important information to include in time since death estimations is the amount of body mass of a corpse that can be lost to the larvae of blowflies during the first few days of decomposition. As much as sixty percent of the body mass can be consumed by maggots in a relatively brief time period (Greenberg and Kunich, 2002). This rapid loss of soft tissue to insect activity could visually appear similar to bacterially-induced breakdown of tissue that takes a much longer time. Key indicators such as bone exposure, loss of viscera, and lack of decomposition fluid must be interpreted within the proper context. If the environmental conditions are favorable to blowflies, then maggot activity should be factored into the scenario. Other insects that inhabit remains during this phase of decomposition include cockroaches, lice,

ants, bees, and wasps (Haskell et al., 1997). Knowledge of the typical behavior of these species allows investigators to more accurately determine the post-mortem interval.

Accumulated degree days (ADD)

Researchers have a multitude of ways to describe time since death. Older literature (e.g. James and Knight, 1965) referred to this time period in number of days since death, or total hours since death. More recently, accumulated degree days (ADD) have become increasingly prevalent as a standardized unit of measure for postmortem interval (Edwards et al., 1987). This is because ADD are seen as a more uniform measure to discuss time since death as it attempts to account for the differences caused by temperature variances at different locations. Accumulated degree days are summations of temperature over time, and represent the thermal energy required for the chemical and biological processes of decomposition (De Donno et al., 2014).

Forensic entomological studies use accumulated degree days extensively in their research, as temperature and insect development have a strong correlation (Anderson, 2000). For use in these studies, entomologists developed an alternate calculation method that ties accumulated degree days to a given insect growth stage as opposed to calculating based strictly on average daily temperatures (Anderson, 2000). Some limitations exist with this method. The basic principle behind this correlation is an assumed linear relationship between temperature and development (Anderson, 2000). Insect development can be accelerated or delayed, however, by temperature extremes. Thus, the ADD that is needed to reach a certain stage of development can vary with differing temperatures, particularly temperature extremes (Anderson, 2000). This vulnerability to temperature extremes does not completely prevent use of insect development to estimate PMI; it simply requires that the forensic scientist be aware of how various temperatures will affect overall development and subsequently require a less linear calculation of accumulated degree days. This will be discussed further in the following chapter.

ADD is calculated by taking the high and low temperature of each day to find an average temperature for that day, and then summing each consecutive day (Miller, 2002). If the temperature falls below zero degrees Celsius on any day, a value of zero is entered into the calculation; negative values are not used (Miller, 2002). Approximately 1285 +/- 110 accumulated degree days are required for a body to completely decompose, with complete soft tissue decomposition defined as the cessation of volatile fatty acid production (Vass et al., 1992). In order to use accumulated degree days to estimate time since death, where the number of days is the unknown factor, Vass (1991) suggests measuring the average daily temperature over one week, and then dividing that into 1285 to determine a maximum number of days since death. This method becomes increasingly accurate the closer a body is to skeletonization, because it is more likely that the body will have been decomposing for a longer period of time (Miller, 2002). ADD has been shown to be less accurate for narrower PMIs, and cumulative degree hours are suggested as an alternative for less decomposed remains (Vass et al., 2002). ADD is still recommended in long PMIs, and in complex situations, such as burials (Vass et al., 2008).

Cumulative degree hours (CDH)

Cumulative degree hours further refines the accumulated degree days concept. Accumulated degree days work well when describing longer post-mortem intervals, but have a potentially wide range. When discussing a body that has been decomposing for several months, the several days over or under-estimation given by accumulated degree days does not critically impact casework. Narrower estimating techniques are beneficial, however, when attempting to determine the post-mortem interval of a body that has been decomposing for a shorter period of time (Vass et al., 2002). Rather than using a 24 hour scale, in calculating CDH, the average temperature in degrees Celsius is added for each twelve hour interval in the decomposition process (Vass et al., 2002). Similar to calculation of accumulated degree days, temperatures

below zero degrees Celsius are counted as a value of zero, and negative values are not used.

Measuring the temperatures at smaller intervals allows for greater accuracy, but does limit the technique to cases in which the body has not been decomposing for an extended period of time.

Accumulated degree hours (ADH)

The increasing frequency of use of ADD, particularly in the entomological literature, prompted scientists to expand upon and refine the concept. Similar to ADD, accumulated degree hours also first appeared in agricultural studies (Greenberg and Kunich, 2002). The purpose of accumulated degree hours was to aid in finding the optimal time to apply insecticide to crops to limit agricultural pests based on their developmental stages (Greenberg and Kunich, 2002). This function is also dependent upon an assumed linear relationship between temperature and insect development. Determining the total ADH required for complete maturation of an insect requires adding the number of hours from egg to adulthood and multiplying that quantity by the temperature in degrees Celsius, after subtracting the developmental threshold temperature (Greenberg and Kunich, 2002). The developmental threshold temperature is the lower boundary; it is the temperature at which insect development will cease. The first application of ADH to a forensic case was a homicide from 1984 (Greenberg and Kunich, 2002). Entomologists in this case started with the total accumulated degree hours needed to reach full maturation for an insect species present at the crime scene and then subtracted each day's calculated ADH (by multiplying temperature by time) in order to work backwards and determine a likely date of oviposition for the insect species (Greenberg et al., 2002).

Since this initial use, some limitations to ADH have been noted. The most significant issue with accumulated degree hours revolves around the fact that the number of accumulated degree hours necessary for a given species to develop from egg to adult was determined in a scientifically controlled laboratory under precise conditions, and stable temperatures (Greenberg

et al., 2002). Crime scenes, to the contrary, are very rarely in stable, controlled conditions, which can affect the rate of insect development, and thereby confound a proper post mortem interval estimate. In addition, other environmental factors, such as submersion of maggots in water, presence of multiple species, or the presence of drugs in the corpse may all affect insect development and calculation of accumulated degree hours (Greenberg et al., 2002). Given the strengths and limitations of ADD, CDH, and ADH, there is no singular best method that can be unilaterally applied to all situations. Each scenario should be evaluated on a case-by-case basis.

Stage-based scoring systems

Observing the visual changes of the body and noting the state of decay is used to determine the post-mortem interval in forensic and research contexts (DiMaio and DiMaio, 2001). The specific stages of decomposition represent a continuum and their definitions in each system were created based on information gleaned from specific studies. As such, they frequently differ between researchers (Galloway, 1997, Megyesi et al., 2005, Marks et al., 2009).

Megyesi and colleagues (2005) developed the most widely applied stage based scoring system. In their method, morphological indicators of decomposition such as abdominal color changes, skin slippage, bloating, and bone exposure are correlated with a point value. The remains being examined are divided into three segments: the head and neck, trunk, and limbs. Each area is evaluated and assigned a point value score. The scores from the three regions are then added together to determine the total body score (TBS). This TBS is then entered into a regression equation which results in an estimated number of accumulated degree days, corresponding to the time since death (Megyesi et al., 2005), such that

$$ADD = 10^{(0.002 \cdot TBS \cdot TBS + 1.81)} \pm 388.16.$$

The TBS has been incorporated into many decomposition studies as a standardized way to describe the physical changes seen during the decomposition process (Dautartas, 2009, Simmons

et al., 2010, Parks, 2011, Metcalf et al., 2013, Smith, 2015). This system requires no equipment, and is designed to be easy to implement (Megyesi et al., 2005). The TBS system has been criticized for not including scavenger behavior (Smith, 2015), only focusing on surface placements (Johnson, 2015) and for having errors in the regression formula (Moffat et al., 2016). Despite these shortcomings, the TBS system continues to be applied in research contexts, in part because there is no other system available that is as widely known or easily used.

Animal models in decomposition research

When human remains are not able to be used in decomposition research, various types of animal models including pigs, dogs, mice, and rabbits have been used (Payne, 1965, Simmons et al., 2010, Metcalf et al., 2013, Beck et al., 2015). Pigs are the most frequently used proxy (Morton and Lord, 2006, Anderson et al., 2013).

Domestic pigs do have some parallels to humans. They have coarse hair as opposed to fur, and their skin thickness is closer to humans than other animal proxies. These factors alone, however, do not mean that domestic pigs can be used as a direct substitute for humans without validation.

Factors such as body size have been documented to impact the pattern or rate of decomposition (Sutherland et al., 2013), yet some studies that utilize pigs use juvenile individuals which are much smaller than the average adult human (Anderson et al., 2013). Payne's 1965 paper documents an early scavenging study utilizing porcine remains. He studied arthropod succession during the summer months, estimating the number and type of insects present. This paper is frequently cited to support the use of pig remains in place of human remains (Anderson and VanLaerhoven, 1996, Campobasso et al., 2001, Carvalho and Linhares, 2001, Grassberger and Frank, 2004, Morton and Lord, 2006). While Payne does argue that his findings can be applied to medicolegal questions concerning human remains, he does not provide

any biological reasoning (1965). He makes no attempt in his paper to establish that pigs are similar enough anatomically to humans to provide usable data; instead, he discusses that his choice of study subject was due to their ease of observation and being able to obtain enough subjects of “large” body size compared to the rats, mice, and chipmunks he had previously used (Payne, 1965).

Despite the lack of comparative studies, the use of domestic pigs as models for humans has expanded in recent years. Domestic pigs have been used to determine if brush fires could leave a characteristic signature on skeletal remains throughout the decomposition process (Fernandes, 2011). They have also been the subjects of a study on the timing of fractures (Wieberg and Westcott, 2008). Reeves (2009) and Morton and Lord (2006) studied scavenging with pig remains. Pigs have routinely been used in entomology studies to determine the rate and pattern of arthropod succession (Anderson and VanLaerhoven, 1996, Campobasso et al., 2001, Carvalho and Linhares, 2001, Grassberger and Frank, 2004). Another study used pigs as a human proxy to examine the effect of embalming on decomposition and insect activity (Keaton, 2012). Lynch-Aird and colleagues (2015) investigated the impact of hanging on decomposition and insect activity through a pig study. Body size and its effect on the decomposition sequence were analyzed by Sutherland and colleagues (2011), again using a pig proxy. Domestic pigs are also becoming more common in the soil ecology literature for microbial studies (Howard et al., 2010, Spicka et al., 2011, Anderson et al., 2013, Meyer et al., 2013). Studies of volatile organic compounds (VOCs) have also been conducted with pig proxies (Stadler, 2013). In each of these studies, the authors stated that the conclusions drawn from their research could be immediately and directly applied to cases involving human remains.

The few studies that have directly compared humans to domestic pigs have come to varying conclusions. Cablk and colleagues (2012) found that different VOCs were produced from decomposing pig heads to human heads. Parkinson (2009) found that the same bacterial communities existed in the soil beneath decomposing humans and pigs, but that there was much more variation in the human sample. Schoenly and others (2007) demonstrated that similar species of insect were found on both the single human and two pig's remains, all of which were placed at the Anthropology Research Facility. Parkinson and Schoenly highlight similarities between humans and pigs and argue that they can be used interchangeably, while Cablk and colleagues focus on the differences between the two species and suggest that pigs are not a direct replacement for human remains. The variation in their conclusions demonstrates the need for more research that directly compares domestic pigs to humans in respect to multiple variables. These studies also demonstrate the lack of consensus on how much similarity is “enough” between the two species to consider them interchangeable.

Implications for forensic casework

Entomology and decomposition studies are often designed to increase the accuracy and precision of postmortem interval estimations. PMI estimations are subject to the criteria set forth in *Daubert v. Merrell Dow Pharmaceuticals*. These criteria include that forensic evidence should be testable, have a known error rate, be peer-reviewed, and be accepted by the specific scientific community (Baque and Amendt, 2013). *Daubert* does allow for use of new techniques that have not yet been peer-reviewed or gained “general acceptance” (Grivas and Komar, 2008). Studies involving pig proxies are generally accepted and are peer-reviewed, but without any validation studies comparing them to humans, it is impossible to have a known error rate. And general acceptance, as set down by *Frye v. the United States*, is a vague standard, which is why it has been since superceded by *Daubert* in federal court cases (Imwinkelreid, 2000). The decision

in *Daubert* explicitly revolves around empirical testing of hypotheses. The admissibility of scientific evidence rests on the strength of the validation or falsification of the scientific principles being introduced (Imwinkelreid, 2000). For this reason, it is imperative that if forensic anthropologists and other forensic specialists are going to present conclusions drawn from data from pig studies as scientific evidence then they must be able to empirically demonstrate that their conclusions are valid and empirically supported.

Similarly, *Kumho Tire v. Carmichael* sets standards for expert witness testimony. It recommends that any expert testimony (scientific or technical) be held to the same rigorous standards as *Daubert* sets for physical evidence (Grivas and Komar, 2008). This decision does not require that all expert testimony meet all of the *Daubert* criteria as experts from different fields may have other, but equally standardized and valid, means of arriving at conclusions besides through the scientific method (Sanders, 2001). The implication here, however, is that expert testimony could be called into question when using information gleaned from pig studies. Even if presented as technical expertise and not scientific, the onus is still on the expert witness to demonstrate that their information is reliable. At a minimum, direct comparison studies between humans and domestic pigs strengthens any information presented in court.

As postmortem interval estimations could be presented at trial, it is crucial to maintain high standards for decomposition research. A thorough understanding of decomposition is needed in order to make the most accurate postmortem interval estimations. In addition to the biochemical processes of soft tissue decomposition that have been discussed in this chapter, insect activity is another major category of variables that can heavily impact rates of decomposition and postmortem interval estimation. The following chapter discusses the basics of

forensic entomology and its application to the research presented in this dissertation. The final literature review chapter provides the theoretical framework for this research.

Chapter III. Insects and the Postmortem Interval

Forensic entomology is the application of the study of insects to legal matters (Catts and Goff, 1992). This field of inquiry can be divided into three major subspecialties: urban, stored product, and medicolegal. The subspecialty of interest here is medicolegal, or medicocriminal, forensic entomology (Catts and Goff, 1992). The most frequent task of medicolegal forensic entomology is the use of insects to estimate the postmortem interval (Catts and Goff, 1992). Estimation of the minimum postmortem interval (PMI) is routinely calculated by determining the age of immature insects found on or near human remains (Baque and Amendt, 2013). The success of this method relies on the correct identification of species, proper understanding of the typical growth and development patterns of the larvae, and knowledge of a plethora of environmental factors that can impact the timing of oviposition or the progression of development. Another often used method for postmortem interval estimation is succession based. This method relies on the identification of two definitive taxa, one giving a minimum PMI and the other a maximum (Matuszewski et al., 2010). For this method, it is imperative that arthropod succession data be available for the specific locality and season of interest.

Species

Insect larvae will vary in their biology and development. For this reason, precise and accurate species identification is the foundation for accurate determination of larval growth stage and therefore, minimum time since oviposition (Amendt et al., 2004). Although there are multiple groups of insects that impact decomposition, two orders actively accelerate the breakdown of remains. These orders are Diptera and Coleoptera, and much of the literature revolves around proper identification of species from these groups (Campobasso et al., 2001).

Species identification is typically accomplished using morphological traits, but this requires specialized knowledge of insect anatomy and taxonomy (Amendt et al., 2004, Mazzanti

et al., 2010). Keys are widely available, but there are few experts that can identify larvae to the species level given the lack of morphological variation in early development (Amendt et al., 2004). Instead, they must be reared to adulthood for taxonomic identification (Amendt et al., 2004). However, it is not always possible to collect and save live larvae for rearing to adulthood, and this is a time-consuming process that may not be amenable during a criminal investigation (Mazzanti et al., 2010). This is why both adult and immature specimens should be collected for analysis. However, care should be taken not to extrapolate that larvae of a species are present simply because adults of a species are collected (Wells and Smith, 2013).

Another option for species identification of larvae is through DNA typing (Amendt et al., 2004). In addition to aiding in identification, genetic information can be useful for understanding the complexity of estimating the developmental age of the insect (Faris et al., 2016). Even within the same species, genetic differences in development patterns have been documented, and this needs to be considered when analyzing development patterns (Owings et al., 2014). Use of genetic information is also beneficial when analyzing puparia. These casings may represent the oldest specimens present at the scene, but their morphology is often similar between species (Mazzanti et al., 2010). DNA analysis is not always possible, and puparial DNA degrades over time, so morphological analysis is still recommended along with genetic analyses (Mazzanti et al., 2010). A lack of genetic information in databases may also present a barrier to the use of this method. Although they are frequently found at death scenes, there is far less genetic information on Sarcophagidae (flesh flies) puparia compared with those of Calliphoridae (blowflies) (Wells and Smith, 2013).

Seasonality

Fly species are also constrained by season (Greenberg and Kunich, 2002, Farrell et al., 2015). Certain blowflies will only appear during the summer months, while others favor cold

weather. In addition to the temperature variation that accompanies seasonal changes, other ecological factors impact oviposition and larval growth. For example, the degree of sun exposure has been shown to affect the pattern of colonization and the probability of oviposition (Carvalho and Linhares, 2001, Amendt et al., 2004). Photoperiod, or the length of daylight and darkness each day, also impacts the rate of growth and development of larvae (Nabity et al., 2006). Rain may also cause a delay in oviposition, or even drown immature larvae (Amendt et al., 2004, Anderson and VanLaerhoven, 1996). The combination of colder temperatures and reduced sunlight in the winter also leads to diapause, or the period in which growth and development of insects is suspended (Amendt et al., 2004). Humidity is another seasonal factor that can affect insect activity. Higher humidity is correlated with more rapid soft tissue decomposition, which will limit the amount of time flies have to oviposit (Carvalho and Linhares, 2001). Many necrophagous species of flies are not known to oviposit on dried or mummified tissue; seasons with high humidity also may lead to higher incidence of desiccation (Campobasso et al., 2001).

Seasonality will also impact the pattern of insect succession (Carvalho and Linhares, 2001). The lowest number of insects as well as the fewest species are anticipated in colder months, while a greater diversity and higher population numbers are expected in the spring and summer (Campobasso et al., 2001, Carvalho and Linhares, 2001).

Geography

Another key set of variables impacting proper entomological analysis is contained in geographic location. Some forensically significant species are constrained by region (Greenberg and Kunich, 2002). Different ecological zones will also harbor different numbers of recurring species as opposed to those that only oviposit once. Coastal and temperate zones tend to have more recurring species than arid or tropical ecosystems (Schoenly, 1992). In addition, populations of the same fly species may have different minimum threshold temperatures, and

thus two geographically separated larval populations would develop at different rates even under the same temperature conditions (Amendt et al., 2004). Intraspecific variation in adult fly behavior has also been shown to correlate with region. For example, black blowflies are not active in Texas during the summer months, but are active during the summer in the northern United States (Catts and Goff, 1992). Fly species from different territories will also undergo diapause, or an interruption of development, at different rates (Amendt et al., 2004). For example, the critical day length will be longer in northern populations than southern populations (McWatters and Saunders, 1998). This means that northern populations will have to be exposed to longer periods of sunlight before they will undergo diapause compared to their southern counterparts.

The availability of site-specific data must also be considered. The majority of entomological studies examining arthropod succession and development have been conducted in temperate regions (Catts and Goff, 1992). Few studies have been done in the tropics, and studies from arid climates are rare (Catts and Goff, 1992). When regionally appropriate data are available, the researcher must be careful to use taxonomic keys and development charts that are specific to the area in question.

In addition to considering region of origin, the more specific location should also be considered. Different species have been identified in rural versus urban habitats. Indoor locations may also harbor different species than outdoor locations (Catts and Goff, 1992, Farrell et al., 2015). Greater species diversity should be expected in outdoor settings (Farrell et al., 2015). Fewer flies may be able to access remains indoors, and smaller maggot masses may be expected. This in turn potentially slows larval development as less metabolic heat is generated (Reibe and Madea, 2010). Even within the same region, different outdoor environments will still favor

different insect species. For example, one study documented different frequencies of various fly species in pine-oak forests, hornbeam-oak forests, and alder forests in Central Europe (Matuszewski et al., 2010). Open-air sites have also shown differences in arthropod community composition when compared to forested areas.

Growth and development

Once the species of insect has been properly identified, often the next step is determining the age of the specimen in question. This is where specific knowledge of the growth and development patterns of forensically significant insects becomes crucial. Most entomologists are able to easily identify the growth stage of an immature insect, but may have difficulty determining how long the insect has been at that particular growth point (Faris et al., 2016). This is why it is imperative to understand the variation in growth patterns among various species, as well as the factors that can cause development to occur outside of typical parameters.

Development stages from egg to adulthood include three larval or immature stages referred to as the first, second, and third instar, respectively (See Figure 1). Subsequently, the larva will move away from the feeding area and enter the pre-pupa and then pupa stage before emerging as an adult (Faris et al., 2016). By the time the larvae have reached their second instar, they will aggregate together to form a feeding assemblage commonly referred to as a “maggot mass” (Heaton et al., 2014). This mass is beneficial to the larvae as it increases the efficiency of their feeding behavior and the metabolic heat produced by the mass insulates individual larvae from negative effects of decreases in ambient temperature (Huntington et al., 2007).

To properly age a larval specimen, length and/or weight measurements should be taken, and the stage of development (first, second, or third instar) should be recorded (Amendt et al., 2007). It should also be determined if the larvae are feeding or post-feeding. The temperature at which the larvae developed should be determined, and then the size and feeding stage can be

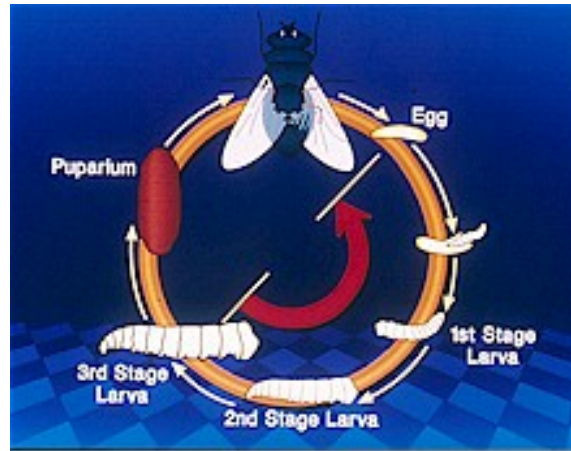


Figure 1: Life cycle of a blowfly (<https://www.flickr.com/photos/brettlider/72767638/>)

correlated with known larval ages for the specified temperature range (Amendt et al., 2007). It should be noted that larval length will shorten immediately before pupation, and certain methods of killing larvae can also alter their length (Haskell and Williams, 1990).

Temperature

Temperature has a significant effect on larval development (Anderson and VanLaerhoven, 1996). All of the methods for determining the age of larvae are based on the fact that ambient temperature determines the rate of development (Amendt et al., 2004). This relationship is assumed to be a sigmoid curve, with a linear segment in the middle range, along with upper and lower boundaries outside of which larval development stops (Greenberg and Kunich, 2002, Baque and Amendt, 2013). It is critical to note that although the relationship is not linear for all temperature values, many studies simplify their discussions and focus only on the linear aspects (Baskerville and Emin, 1969). The optimal temperature range, as well as the lower and upper boundaries, are species specific (Heaton et al., 2014). It should also be noted that the minimum temperature for larval development is not always equivalent to the minimum temperature required for oviposition. It may be possible for eggs to be laid at a given temperature, but for it to still be too cold to have the larvae survive and grow (Nabity et al.,

2006). Generally speaking, most forensically significant species will have a faster rate of development at higher ambient temperatures until the upper temperature threshold is reached (Heaton et al., 2014).

Temperature fluctuations are also critical. Larval development at a constant temperature will differ from development that takes place during large temperature changes (Clarkson et al., 2004). Larvae reared at constant temperature tend to develop more rapidly than those exposed to temperature fluctuations (Byrd and Allen, 2001). In order to correctly assess growth and development, the patterns for a specific species at a given temperature range must be known. This is often difficult, however, as few studies exist that track the development of larvae at low temperatures, and studies frequently include too few replicates to be statistically reliable (Nabity et al., 2006).

Maggot masses can generate a large amount of metabolic heat; this heat can impact larval development and survival just like ambient temperature (Amendt et al., 2004). Internal body temperatures have been recorded as much as 22 degrees Celsius higher than ambient during peak maggot activity (Catts and Goff, 1992). Heat generated from maggot masses can produce temperatures that are too high for larvae to survive or feed efficiently (Heaton et al., 2014). Possibly to avoid this problem, large larval masses will disperse into smaller aggregates as food and space allows. The total amount of metabolic heat produced by the mass will also be influenced by the density of the mass (Goodbrod and Goff, 1990) as well as the quantity of food available (Charabidze et al., 2011). Biological variation in species will also influence maximum potential heat generated, as species with larger larvae tend to produce more heat (Rivers et al., 2010).

Understanding mass dynamics is critical, as standards of larval growth may have been

developed from larvae reared in masses. If the heat differences between ambient and mass temperatures are not taken into account, the age of the larvae and therefore the minimum postmortem interval will then be incorrectly estimated (Heaton et al., 2014). Maggot mass temperature is also subject to change based on fluctuations in ambient temperature. Huntington and colleagues (2007) reported that maggot mass temperature dropped considerably when remains were placed into a morgue cooler. Even with a sizeable, active mass, the temperature dropped low enough to potentially slow the larvae's rate of development.

Toxicology

A relatively new sub-specialty of entomology, entomotoxicology examines the applicability of toxicology related analyses to carrion-feeding insect larvae. A primary task of entomotoxicology is to understand the impact of these drugs and toxins on the growth and development of larvae, and the implications these affected growth patterns may have for using larvae to establish a post-mortem interval (Introna et al., 2001). These analyses are also sometimes used to detect drugs and other toxins in the tissues upon which the larvae fed (Introna et al., 2001).

As this is a still developing area of study, not all toxins and drugs have been assessed. Those substances that are more frequently encountered in forensic cases have been the most widely examined. Morphine (Bourel et al., 2001), diazepam (Carvalho et al., 2001), barbiturates, benzodiazepines, antidepressants (Introna et al., 2001), cocaine, amphetamines, and opioids/opiates (Gosselin et al., 2011) have all been successfully detected in larvae. Not all of those drugs listed have been evaluated for their impact on the growth and development of the maggots (Gosselin et al., 2011. Murthy and Mohanty, 2010). In addition, the feeding behavior and stage of development when the larvae ingest the intoxicated tissue also impacts how the development might be altered (Gosselin et al., 2011, Verma and Paul, 2013). Larvae that ingest

intoxicated tissue early in their development will be more profoundly affected, as will larvae that consume larger amounts of altered tissue. The type of drug also determines if the impact will be to accelerate or suppress larval growth. Goff and colleagues (1989) demonstrated that insects reared on tissue containing heroin or cocaine would lead to more rapid larval development. In contrast, Bourel et al. (1999) showed that morphine could lead to an underestimation of PMI by as much as 24 hours. The pesticide malathion has been documented as delaying the onset of insect activity by three days (Gunatilake and Goff, 1989).

Several studies have criticized the utility of insects as a measure of the concentration of a toxin in the tissues of the deceased (Traqui et al., 2004, Gosselin et al., 2011). The absorption rate of the toxins is not consistent among all larvae, and the site on the body from which the larvae were collected can impact the results of the analysis significantly (Murthy and Mohanty, 2010, Gosselin et al., 2011). There is also a lack of a standard storage protocol, and disagreement about the interpretation of the results of detected drug concentrations (Gosselin et al., 2011). For these reasons, there has been a shift to emphasizing the importance of understanding how these toxins affect the larvae (and thus impact PMI estimation) instead of trying to use them as a proxy for the deceased tissue (O'Brien and Turner, 2004, Traqui et al., 2004, Verma and Paul, 2013).

Predatory species

Another potential barrier to larval development is the presence of predators or parasites that feed on the necrophagous species (Campobasso et al., 2001). Significant predation can thin the population of larvae and interfere with proper estimation of postmortem interval (Campobasso et al., 2001). In addition to necrophagous and predatory species, omnivorous species also need to be considered. These include ants, bees, and wasps, which may feed both on the larvae of other species as well as on the remains themselves (Catts and Goff, 1992). In the absence of predators, fly species have a greater rate of survival, pupation, eclosion and fecundity

(Faris et al., 2016). Within a single species, cannibalistic fly activity has also been recorded (Farrell et al., 2015).

Intraspecific and interspecific competition, while somewhat different from predation, can also impact the survival and development of larvae by affecting their ability to feed (Heaton et al., 2014). In addition to competing for access to food, different species have varying upper and lower temperature thresholds, and some species may be able to outcompete others simply by withstanding a particular temperature. In some cases, it has even been speculated that larvae will aggregate in particular patterns to raise the temperature to outcompete other species present (Richards et al., 2009)

Insects and decomposition

Insect activity is one of the most important factors affecting decomposition. Insects accelerate the decomposition process (Gonzales et al., 1954). Ants, blowflies, beetles, and cockroaches all affect decomposing tissue. Blowflies are typically the first insects attracted to the body; they can be observed on a corpse minutes after deposition (Campobasso et al., 2001). Oviposition from these species can be delayed however by impeded access to the body, cold temperatures, or placement at night when fewer species are active (Nabity et al., 2006). Insects lay eggs around the orifices of the mouth, nostrils, eyes and genitals, and any open wounds. Eggs then hatch into maggots within eight to fourteen hours (Campobasso et al., 2001).

Maggots disrupt soft tissue, burrowing into the flesh. Larvae also decompose proteins in the soft tissue, which leads to liquefaction of the area (Evans, 1963). Large numbers of maggots are generally produced, and the collective group is often able to consume much of the soft tissue within a short period of time. Maggots also help to disseminate bacteria throughout the body as they travel while feeding (Lord, 1990). Metabolic heat generated by the maggot mass further stimulates decomposition (Mann et al., 1990, Huntington et al., 2007).

As much as the insects impact the progression of decomposition, the stage of decomposition also affects the type and amount of insect activity possible. Flies are typically chemically attracted to remains early in the decomposition sequence, and many species will not oviposit after tissues have dried out (Campobasso et al., 2001). Similarly, multiple beetle species do not appear until later stages of decomposition (Catts and Goff, 1992). The overall number of insects present will also be dependent on decomposition processes. In seasons when decomposition starts later and proceeds more slowly, there is a longer period when chemical attractants are given off, and thus the total number of insects over the entire period of decomposition may be greater in spring and fall, even though large numbers are attracted to remains quickly in favorable summer weather (Matuszewski et al., 2010).

Research experiments with carrion have shown that only some insect taxa behave consistently when patterns of decomposition vary (Matuszewski et al., 2010). These more consistent taxa, such as blowflies, are therefore recommended as the focus of PMI estimations. Behavioral consistency includes first appearance on remains in the same stage of decomposition, regardless of season or length of time in that decomposition stage. The second characteristic is abundance of the taxon (Matuszewski et al., 2010). Abundance of a taxon is considered because it informs the researcher as to the probability of its presence at a death scene.

Patterns of insect succession may also be used to estimate PMI, particularly for remains that are in later stages of decomposition (Anderson et al., 1996). Succession refers to the predictable pattern of species replacement in given ecosystem (Gruner et al., 2007). Multiple studies have documented that blow flies have a predictable faunal succession correlated with stages of decomposition (Greenberg, 1991, Catts and Goff, 1992, Schoenly and Haskell, 2000, Tabor et al., 2004). In addition to the flies drawn specifically to the remains, there is also a

succession of predatory insects that come to feed on the necrophagous species, and these predator patterns can be used to help estimate PMI (Sharanowski et al., 2008). Succession can be determined from analysis of adult fly, larval, or puparial specimens (Archer and Elgar, 2003).

As different species are more abundant at specific decomposition events, the diversity of insects present and the relative abundance of each type can be used to help establish a timeline (Amendt et al., 2007). Various species are also more likely to be present in specific geographic locations, so entomological succession evidence can be used to help identify location of death as well as timing (Gruner et al., 2007). More work is still needed, however, to develop sufficient references for each geographical region concerning succession patterns (Amendt et al., 2007). The literature currently only has a few statistically analyzed, quantitative succession studies on forensically significant fly species (Gruner et al., 2007). Succession is also environmentally (ambient temperature and microenvironment are critical) and seasonally constrained, further increasing the need for multiple studies in a variety of locations (Tabor et al., 2004, Sharanowski et al., 2008).

Collection and preservation in forensic contexts

Proper species identification and determination of growth stage occurs during analysis of insect samples. Prior to examining any entomological evidence, however, the specimens must be collected, preserved, and often transported to an expert. Standard collection procedures were followed during the data collection phase of this dissertation to ensure quality of information. If proper, standard collection procedures are not followed, or if specimens are not correctly preserved, vital information could be lost or destroyed (Catts and Goff, 1992). Suggested collection procedures have been outlined by multiple authors (Catts and Goff, 1992). These procedures include instructions for killing and preserving larvae as well as collecting and rearing larvae to adulthood (Farrell et al., 2015). Copious notes should also be taken of the scene, and

environmental data should be collected. In part, this is because the absence of an abundant taxa from a scene may provide critical information about when and where remains have decomposed (Matuszewski et al., 2010). Following established guidelines is also considered best practice and helps to preserve not only information and chain of custody, but also protects the living specimens which should be treated ethically (Amendt et al., 2007).

During collection at the scene, personal protective equipment should be worn to prevent contamination. The tool kit used by the collector should include vials, labels, pencil for writing labels, and a variety of implements for catching both adult and larval specimens (Amendt et al., 2007). Adult terrestrial specimens can be collected using forceps, while flying insects can be collected either using a standard net or sticky traps placed approximately one meter away from the remains (Amendt et al., 2007, Haskell and Williams, 1990).

Specimens that are already dead can be stored in vials containing 70-95% ethanol (Amendt et al., 2007). Living specimens should be transported in temperature and humidity controlled containers, when possible. Living larvae should then be reared in the laboratory under temperature and humidity controlled settings, with all environmental data carefully recorded (Amendt et al., 2007). Eggs that are not intended to be kept alive for rearing to adulthood can be immediately placed into 70-95% ethanol, while larvae need to be killed using hot (but not boiling) water or a solution of kerosene, acetic acid and ethanol before being transferred into ethanol for long term storage (Haskell and Williams, 1990). Adults should ideally be collected live and then put into a freezer (held at approximately 20 degrees Celsius) for killing, and then preserved either in ethanol or by pinning (Amendt et al., 2007).

Multiple locations on the remains should be utilized for sampling. At a minimum, these sites should include the natural orifices of the body, any traumatic wounds, the soil directly

underneath the remains, and the folds of any clothing or covering surrounding the body (Haskell and Williams, 1990, Amendt et al., 2007). It is also recommended to search the area around the remains up to two meters away to track any third instar larvae that may have moved away from the body to pupate (Haskell and Williams, 1990). A control sample of soil should be collected from outdoor scenes (Amendt et al., 2007).

Animal models in entomology studies

As mentioned in the previous chapter, animal models are sometimes used in entomology studies when researchers are unable to use human cadavers. One of the earliest studies of arthropod succession in the southeastern United States used domestic dogs as a proxy (Reed, 1958), however domestic pigs are the most often used proxy in entomology studies (e.g., Anderson and VanLaerhoven, 1996, Huntington et al., 2007, Schoenly et al., 2007, Reibe and Madea, 2010). Some of these studies (Huntington et al., 2007) also incorporate human remains through individual case studies, but other researchers (Reibe and Madea, 2010) rely solely on the use of a porcine model. For example, Simmons et al. (2016) examined differences in decomposition rates between pigs placed at five locations in four countries. In this study, they present a hierarchical order of decomposition rates for each location, but do not address if humans would exhibit the same pattern. Results from entomological studies are often discussed in terms of their implications for PMI estimation. Rarely do the authors discuss whether or not a measure of error would be introduced by using data collected from pigs and applying it to cases involving human remains. This is potentially problematic as the original intent of these studies (e.g. Huntington et al., 2007, Reibe and Madea, 2010, Vanin et al., 2013) is often to address a source of error in PMI estimation. This may be trading one source of error for another. The complexity of interpreting results from studies based on pig models is demonstrated by Anderson and VanLaerhoven's 1996 project on insect colonization.

Anderson and VanLaerhoven (1996) used domestic pigs to document insect succession in British Columbia. Pigs were laid out in an open, sunlit area for the purpose of building a database of insect colonization for the region. The authors noted that the total colonization time lasted longer throughout the decomposition sequence than what had been reported for other areas (Anderson and VanLaerhoven, 1996). This difference in the duration for each stage of decomposition was attributed to geography. It is unclear, however, if the variation observed among succession and decomposition patterns is solely due to regional differences. In addition to different geographic locations, some of the comparative studies used substantially smaller pig carcasses (Early and Goff, 1987). Although this size difference is noted, Anderson and VanLaerhoven dismiss it as a likely cause of the variation, citing a study done in East Tennessee by Rodriguez and Bass (1983) showing similar decomposition patterns to Early and Goff's (1987) study in Hawaii. The Rodriguez and Bass (1983) study, however, utilized human cadavers as opposed to pig remains. Hawaii and East Tennessee also have different climatic patterns. The fact that human cadavers in one study demonstrated similar decomposition patterns to pigs in another study does not mean that size variation is negligible. There are too many variables interacting with each other simultaneously that impact how decomposition progresses and how insects colonize and utilize the remains to easily determine a sole cause of variation.

Anderson and VanLaerhoven are not the only researchers to use pig models to examine insect colonization. Citing this 1996 study as an example and justification for using pig remains, Eberhardt and Elliot conducted a similar project in 2008 to establish colonization and succession patterns for three habitats of the Auckland in New Zealand. Similar succession studies were done in Colombia, (Martinez et al., 2007), southwest Virginia (Tabor et al., 2004), Saskatchewan (Sharanowski et al., 2008), and Florida (Gruner et al., 2007). Each of these cited either the

Anderson and VanLaerhoven 1996 paper, or in the case of Gruner and colleagues, one of the subsequent succession studies that relied on the 1996 study as a model (Tabor et al., 2004).

While this study has clearly set a precedent for subsequent research, the simple fact that it used pig remains should not be seen as unquestionable proof that a pig model is sufficient for entomological investigations.

As this literature review has shown, entomological activity has a profound impact on rates of decomposition. While this dissertation is not solely or specifically focused on detailed entomological analyses, the effects of larval activity on observed patterns of decomposition and resulting total body scores will be addressed. The next chapter will discuss theoretical basis for this dissertation.

Chapter IV. Chaos Theory, Non-linear Systems Theory and Complexity Science

“Chaos Theory” is one of several popular names of a collection of perspectives aimed at understanding the dynamics of unpredictable systems (McGlade and van der Leeuw, 1997). Another term frequently used for this broad collection of ideas is non-linear systems theory, though the terms are not synonymous (Haigh, 2002). Rather, both of these terms, along with catastrophe theory, systems theory and nonlinear dynamics are all variations on what can be captured under the umbrella of “complexity science.” All of these perspectives have been used to attempt to better understand phenomena that are both complicated (having many parts) and complex, meaning having behavior that cannot be easily explained by analyzing individual components alone (Jones, 2015). Wide varieties of research topics ranging from geometry to political science apply these ideas to structure their research (Beekman and Baden, 2005, Williams, 1997). This concept has been applied in archaeology to model culture change over time (Beekman and Baden, 2005).

Terminology use is inconsistent between and within fields that use complexity science perspectives. Presented here are definitions for each term, as they will be used in this dissertation. The name “chaos theory” emerged in the 1960’s for research into deterministic systems that became increasingly unpredictable over time based on sensitivity to initial conditions (Beekman and Baden, 2005). A classic example is weather patterns. Meteorologists realized that changing one small input parameter could lead to vastly different predictions of weather patterns. Non-linearity specifically applies to systemic environments where interrelationships between variables cause unpredictability. Non-linear systems are also open; they are subject to varying degrees of stability based on the introduction of new variables throughout the analytic period. Ecological systems are good examples; the introduction of new

species or environmental change can lead to drastic changes in stability of the overall system. Complex systems describes situations where mutual interactions of many agents can lead to emergent properties within the broader system, such as settlement patterns in archaeological societies (Blakeslee, 2002). Catastrophe theory relates to systems that have few variables but still show surprising or unpredicted transformations or non-linear trajectories depending on their interactions (Beekman and Baden, 2005). Catastrophe theory is frequently applied to abstract mathematical research, as it is difficult to take systems in the real world and simplify them down to only a few key variables.

In an attempt to simplify this discussion, some authors have argued for the use of a broad term to include all of the perspectives defined above. Here again, the terminology is inconsistent. Some authors use “complexity science” to incorporate all of the various perspectives, while others use “systems theory” (Beekman and Baden, 2005). Others (e.g. Rasband, 1990) still use “chaos theory” to mean the broad collection of ideas. Beekman and Baden (2005) suggest the use of the term non-linear systems theory to include aspects of chaos, complexity and catastrophe. Matthews et al. (1999) expand on these inconsistencies by listing non-linear dynamic systems theory, complexity sciences, chaos theory, catastrophe theory and complex adaptive networks as variations on the same theme. These authors argue that the relationships between these variations are either poorly defined or poorly understood, and they provide no definitions or distinctions between them. I will be using the term non-linear systems theory in the manner suggested by Beekman and Baden (2005) as the primary theoretical framework for this research, meaning that I will use the term “non-linear systems theory” to indicate a specific perspective that incorporates aspects of complexity, chaos and catastrophe. I will use the term “complexity science” as the broad collection of perspectives that expands beyond non-linear systems theory.

Non-linear systems have some deterministic aspects; that is, parts of the system that can be well explained and predicted by mathematical equations, but there are aspects that behave unpredictably over time. All non-linear systems are dynamic, which simply means they will change over time (Williams, 1997). Non-linear systems have specific predictable aspects over short periods, but their behavior becomes increasingly divergent and unpredictable as time depth increases. Part of this uncertainty stems from the disproportionate relationship between variables in the system. For example, as applied to this research, temperature does not have a direct linear relationship to insect development outside of a specific threshold, and a drop or increase of a few degrees could mean the difference between normal development, delayed development, or none at all.

Another important component to non-linear systems theory is a sensitive dependence on initial conditions. This means that small differences in parameters in the beginning of the systems emergence (as applied to the research of this dissertation, the system's emergence is the time of death) can lead to large deviations as time progresses (Erwin, 1997, May 2004). Non-linear systems also have an historical characteristic. When looking at a numerical value in a non-linear series, the value at any given time will be at least in part dependent on the previous value (Williams, 1997). This is easily observed in decomposition research; decomposition is a progressive phenomenon. Each individual observation might not perfectly reflect the observation before it, but the prior weather conditions, insect activity, and scavenging activity all help to determine what will be observed next.

A counter perspective sometimes seen in natural and medical sciences (and decomposition research) is reductionism. From this perspective, a complicated and difficult to understand problem can be broken down into increasingly simple parts, and thus solved (Ahn et

al., 2006). This type of approach has also been termed “Newtonian” due to the focus on finding relationships that can be accurately addressed through mathematical equations (Beekman and Baden, 2005). While non-linear systems theory and reductionism address problems differently, they are not diametrically opposed. The main difference is that reductionist approaches focus on single or small subsets of independent variables and their relationship to dependent effects. Systems approaches (including non-linear systems) incorporate the information elucidated by these studies and attempt to integrate them into a more complex whole. It is important to remember that these complex systems with seemingly random motions do follow rules determined by specific variables (Williams, 1997). In situations like decomposition, interaction effects, or the unique effects produced by combining variables, play a key role, but complex behavior can have simple causes.

At their core, non-linear theories are mathematical. First used in mathematics, and then engineering, they are describing a continuous system with discrete observations so that difference equations (which are solvable) can be used in place of differential equations (which are either difficult or impossible to solve uniquely) (Williams, 1997). Physics made use of non-linear dynamics early on, before any of the life or social sciences incorporated those methods (Williams, 1997). A classic first-year physics problem is predicting the path of a bead of water on a hoop. To solve the problem gravity, centrifugal force, and friction must be considered, as well as how each of these forces affect each other (Strogatz, 1994).

Ecology was another field that applied complexity science early. Huisman and Weissing (2001) refer to studies looking at species competition for food resources. These studies examined both the change over time within species based on population growth or decline, and analyzed interaction effects of multispecies competition for food. Hallmarks of a nonlinear system, such as

a cyclical or seasonal component and change over time, are clearly present. There are identifiable deterministic aspects as well, such as the type of food available, and the number and relationship of species in the ecosystem. The application of a non-linear systems approach is beneficial by considering that each of these species does not exist in isolation, but that their ability to access food resources is compounded in the ecosystem by the presence and interaction of other organisms. Hastings et al. (1993) applied non-linear systems theory to ecology specifically because of a focus on sensitive dependence to initial conditions. In their example, the question of population size and stability depended upon the resources available at the start of the observation period.

Ecology also introduced the concept of resilience to non-linear systems. Ecologists noticed that change did not happen consistently; gradual change in a system can be interspersed with periods of rapid change (Folke, 2006). From there, they observed that systems often have a way of absorbing the “shock” of change to be able to continue to function. Folke (2006) notes that this refers to the use of environmental resources, specifically how social relationships or the use of resources from other regions besides the home region enables a system to continue to function according to typical parameters even when there is a distinct change, such as a shortage of a specific food type.

Political science and economics have incorporated non-linear systems theories as well (Kiel and Elliot, 1997). These disciplines face problems with many of the same issues as decomposition research. There is unpredictability, uncertainty, and a lack of proportional response to variable change. Political science often has to contend with “disruptors” or variables that can alter individual behaviors in unpredictable ways (Brown, 1996). This has been applied to the study of voting habits (understanding the individual and group decisions) and the stability of

hostile nations (Richards, 1996, Saperstein, 1996). Non-linear systems theory applied to political science has shown that there is still some predictive ability, but again only in short-term.

The social science application of non-linear systems has been largely descriptive. In sociology it is a branch of post-modern theory and does not revolve around applying different equations or distributions (Kiel and Elliot, 1997). Cognitive psychology has applied complexity science perspectives by modeling cognitive processes, such as olfactory pattern recognition. This examines how memories are formed, adapted, and replaced, and challenges the idea that there are discrete categories of memory. Instead, the flexibility and adaptability of the brain are emphasized and the importance of multiple influences on memory are highlighted (Robertson and Combs, 1995).

Biology and medicine have used the equations developed by complexity science mathematicians to describe diverse systems such as epilepsy, enzyme kinetics, biological signaling and biochemical reaction networks (Walleczek, 2000, Larter et al., 2000). Ahn (2006b) has advocated for the use of complexity science in medicine, but as a complement to Newtonian thought. He makes a distinction between illnesses that are acute and can be well explained by reductionist methods, such as urinary tract infections, and chronic illnesses that can be influenced by many interacting variables, such as diabetes. The life sciences have found this theory base useful because living systems have a lot of internal noise that is impacted by environmental variables (Walleczek, 2000). In decomposition, this is literal. The internal microbial dynamics of the body are themselves a complicated system, and the external environmental components can have a significant impact. Scavenging, for example, can radically alter the progression of decomposition by disrupting insect activity as well as biochemical breakdown processes. Living systems are thermodynamically open, constantly exchanging

matter and energy with their environment (Walleczek, 2000). The same can be said for decomposition.

Non-linear systems theory has been applied to questions in archaeology. The desire to discuss archaeological phenomena from a scientific perspective led researchers to attempt to use models that combine the laws of physics and chemistry with the complexity of living organisms (Allen, 1997). Early models were mostly mechanical; predicated on the idea that a system can be understood and predicted by identifying and understanding the dynamics of its components or causal links. Mechanical models proved ineffective for archaeology for the same reason that they are insufficient to describe decomposition. Only in closed systems that do not allow new energy or matter can there be a single, predictable, inevitable solution. Open systems, such as settlement patterns [or decomposition] consistently have gains and losses of energy and matter, and therefore have multiple possible outcomes (Allen, 1997). More recently, McGlade (2014) has called for a better understanding of the philosophical perspectives encapsulated in complexity science and not just a reliance on modeling in archaeology.

This is not to suggest that there is no predictive power in non-linear systems. Instead, the emphasis is on understanding the dynamics of as many components of the system as possible and combining their effects to better understand the system as an integrated whole. Although open systems may change indefinitely, there may be identifiable patterns such as cyclical or seasonal paths (Allen, 1997). A benefit to applying this theory is that it can improve short-term predictions (Williams, 1997).

Non-linear systems theory has typically been applied in two ways. The first is as a philosophy, as exemplified in Haigh's 2002 paper where she suggests that non-linear dynamics should guide the way nurses think about organizing and evaluating care delivery. This

philosophical approach has also been applied to forensic pathology by “informing the study” of trauma by considering multiple variables and how they may have interacted (Jones, 2015). The second way non-linear systems theory has been applied is as a structure for methodological choices. If a system has non-linear characteristics then the appropriate analyses need to be able to address these complexities. Statistical modeling and time series analyses are the most frequently suggested and used analytical procedures.

Although it has not been widely applied to biological anthropology, non-linear systems theory is particularly well suited to decomposition research as both a philosophical way to think about how decomposition works and as a guide for selecting appropriate statistical methods to understand the system. In attempting to understand and predict decomposition patterns, many individual variables have been studied. The impact of temperature, insect activity, and humidity are all well documented. Understanding these variables in isolation, however, has not provided anthropologists with the tools to be able to consistently and accurately estimate time since death. This is because decomposition as a system is more complicated than the individual mechanisms of its parts. This theoretical base will also help shift the paradigm from decomposition being seen as too complicated to model accurately to a non-linear system that maintains some underlying order. The pattern of decomposition may seem random, but it is still fundamentally determined by underlying principles. The more complex the system, the more random the series will appear to be (Williams, 1997).

There is at least one potential problem to address before applying non-linear systems theory properly to decomposition research. Short-term predictions are more likely to be successful than long-term predictions (Williams, 1997). Therefore, it has to be determined what qualifies as short-term in the decomposition progression. Perhaps this is up to the point of

skeletonization or mummification. Attempting to answer this question may help elucidate what the time ceiling is for accuracy.

Choosing the right mathematical or statistical methods is also critical. Non-linear systems that change over time are time series. Time series is a collection of statistical modeling methods that specifically addresses data that change over time and are affected by multiple variables. Time series can account for seasonality, cyclical variations, interaction effects, and requires testing for random noise that can be confused for significant patterns. These methods have been routinely applied to economic, meteorological and supply data but has yet to be frequently used in anthropology. Time series methods have been applied to biological data. Feng and colleagues used time series analyses to develop models based on climatic variables to predict spikes of foot and mouth disease in livestock (2014). Decomposition research is an ideal area for application of time series methods, as decomposition is impacted by a range of interacting factors and is a time-driven process. The next chapter details the data collection and analytical methods applied in this research.

Chapter V. Materials and Methods

To test the hypotheses that patterns of decomposition will differ between human and pig subjects in terms of soft tissue morphological indicators, insect activity, and scavenger activity a multiple trial project was designed to span three seasons. This chapter describes the sample of both pig and human remains, as well as the data collection and analytical procedures used to evaluate the research questions.

Sample composition

All data for this project were obtained from fifteen human specimens and fifteen domestic pig specimens. Human subjects were utilized through the body donation program administered through the Forensic Anthropology Center at the University of Tennessee, Knoxville. Pig subjects were purchased from a local farm in East Tennessee; the same pig vendor was contracted for each trial.

The body donation program began in the early 1980's and provides an avenue for human remains to be donated directly to the Forensic Anthropology Center at the University of Tennessee, Knoxville specifically for use in forensic anthropology research. The majority of donated individuals are "pre-donors", representing people who complete donation paperwork while still living. Family members or, most rarely, medical examiners, donated some of the individuals. Since 1981, over 1,500 donations have been received. Donors are placed at the outdoor Anthropology Research Facility for the duration of the decomposition process before the skeletal remains are cleaned and accessioned into the William M Bass Donated Skeletal Collection.

Human sample

Human subjects with a known time of death no more than ten days prior to the target date of placement were chosen for this project. Each individual died of natural causes, and none were

autopsied, or had external trauma, as this may have impacted insect activity. Remains were kept in a morgue cooler held at 40° Fahrenheit prior to placement. Weights for the humans ranged from 116 pounds to 235 pounds. There were seven males and eight females. Specific demographic information for each subject is provided in Table 1.

Pig sample

Pig subjects were transported from a local farm to the UT College of Veterinary Medicine. They were sedated preceding euthanasia with pentobarbital (1cc/10lbs). Euthanasia was completed within 24 hours before placement for trials 1 and 2, and within 10 days prior to placement for Trial 3 Winter. Euthanasia was conducted following approval from the University of Tennessee Institutional Animal Care and Use Committee (IACUC). Weights for the pigs ranged from 88 pounds to 150 pounds. There were 6 males and 9 females. Specific demographic information is provided in Table 1.

Placement procedures

The subjects were placed at the outdoor laboratory of the Anthropology Research Facility (ARF), in a section located behind the William Bass Forensic Anthropology building, where no other surface decomposition research had previously occurred. This is an approximately one acre wooded area surrounded by a wooden and chain link fence. Minimal clearing was conducted to create a 2 foot wide walking path and area for placement. As much vegetation as possible was left in the project area to preserve the natural setting. Placement areas of two meters by one meter were cleared of large trees or briars, and three meters were left unaltered in between each placement spot within each trial. Five meters of unaltered vegetation separated each trial. Figure 2 shows the placement area before ground clearing.

Each successive trial moved upslope to prevent any decomposition fluids from contaminating the next area. This allowed for soil samples to be collected in each trial.

Table 1: Demographic information of all human and pig subjects.

Trial 1 Spring 14 Mar 2014	Subject	Research ID	P/M Weight (lbs) Bass Scale*	Sex
	H1	UT116-13D	179	M
	H2	UT115-13D	159	F
	H3	UT113-13D	186	M
	H4	UT114-13D	167	M
	H5	UT112-13D	167	M
	P1	UT107-13D	140	M
	P2	UT108-13D	133	F
	P3	UT110-13D	140	F
	P4	UT109-13D	148	
	P5	UT111-13D	150	
Trial 2 Summer 13 Jun 2014				
	H1	UT117-13D	123	F
	H2	UT118-13D	147	M
	H3	UT119-13D	116	F
	H4	UT120-13D	191	M
	H5	UT121-13D	235	F
	P1	UT122-13D	113	M
	P2	UT123-13D	104	F
	P3	UT124-13D	106	M
	P4	UT125-13D	130	M
	P5	UT126-13D	88	F
Trial 3 Winter 01 Dec 2014				
	H1	UT145-13D	126	F
	H2	UT142-13D	173	F
	H3	UT143-13D	188	M
	H4	UT144-13D	186	F
	H5	UT146-13D	161	M
	P1	UT133-13D	103	F
	P2	UT132-13D	106	M
	P3	UT134-13D	126	F
	P4	UT136-13D	117	F
	P5	UT135-13D	106	F

*all individuals were weighed on the same scale



Figure 2: Trial 1 Spring area prior to clearing.

Human and pig subjects were placed in as straight and continuous of a line as terrain allowed to attempt to keep all subjects in each trial in the same microenvironment. Rabbit subjects were also included in a larger study (Dautartas et al., 2015, Dautartas et al., 2018, Steadman et al., 2018) but are not analyzed as part of this dissertation. The order of the fifteen subjects in each trial was determined with a randomized block design conducted in SAS version 9.3. A block design was used to ensure that two of the same species would not be placed in adjacent plots. The species were not grouped together to allow for clearer analysis of insect and scavenger activity. If the species were grouped together, then differences seen in the presence of insect species or scavenger type could potentially be attributed to location and not sample species. The placement order for each trial is shown in Table 2. Human and pig subjects were not covered with any mesh or cages, which are typically used to deter scavenging activity. Although the research facility is protected from larger scavengers (such as coyotes) by a double fence, smaller scavengers can still significantly impact the conditions of remains. As opposed to deterring their activity, the decision was made to document and analyze patterns of animal

Table 2: Placement order for each trial. H=human, P=pig, R=rabbit.

Trial 1 Spring		Trial 2 Summer		Trial 3 Winter	
Block	Treatment	Block	Treatment	Block	Treatment
1	H	4	P	4	R
1	R	4	H	4	H
1	P	4	R	4	P
2	R	5	P	2	H
2	H	5	H	2	P
2	P	5	R	2	R
4	H	3	H	5	H
4	P	3	R	5	P
4	R	3	P	5	R
3	P	2	R	1	P
3	H	2	H	1	H
3	R	2	P	1	R
5	P	1	R	3	P
5	H	1	P	3	H
5	R	1	H	3	R

scavenging. Human and pig subjects were also placed on top of plastic mesh to allow for the bodies to be rolled for collection of soil samples. The results of the soil studies are part of a separate analysis not presented in this dissertation. Figure 3 shows a cleared placement area with mesh laid down prior to placement.

To help test the scavenging hypothesis, six Moultrie game cameras were placed along the subject placement line, facing the study subjects, to photograph any animal activity during the course of the trial. These cameras were moved if scavenging activity was noted on an individual that was not in the line of sight of a camera. Any movement of cameras was noted in the daily log. Three TinyTag temperature and humidity data loggers were also placed along the line to record ambient environmental data. These data loggers were set to record once per hour.



Figure 3: Placement area with mesh.

Data collection procedures

Data, including photographs, insect samples, and total body scores were collected twice daily until a minimum of 2000 accumulated degree hours (ADH) were reached. Photographs were used to record decomposition changes and evidence of scavenging, such as scratches or wounds opened after placement, for each subject. Adult and larval insect samples were collected in order to assess entomological taxonomic preference for human or pig carrion. Morphological indicators of decomposition, used here as a marker for decomposition progression, were measured by use of the TBS system. The 2000 ADH was selected as the benchmark for data collection to capture the entire period of active decomposition (Vass et al., 2008). After the requisite number of ADH were reached, data collection was continued once daily, then weekly, until most soft tissue decomposition was completed. The cessation of soft tissue decomposition was marked by plateauing scores in the TBS system. This metric was selected to encompass both

individuals who had reached skeletonization and also those individuals where the majority of the soft tissue became mummified.

Photographs

A Nikon digital camera was used to photograph the subjects individually at each data collection event. An overall shot of the entire body and then section shots were done of the head, torso, limbs, hands and feet, and any other significant areas (e.g. evidence of scavenging activity, maggot masses, and close ups of soft tissue decomposition, such as skin slippage, marbling and discoloration.) Each photograph was repeated at least two times to ensure that a clear photograph would be obtained. Inclement weather, such as heavy rain or snow, prevented data collection as the camera was not weather proof. Photographs were taken from as directly of an overhead perspective as possible. Significant sloping in some of the trial areas prevented perfectly perpendicular camera angles in some photographs. A scale was included in the photographs.

Decomposition Scoring

Total body scoring following Megyesi et al. (2005) was conducted on both the human and pig remains. Scoring was conducted by the author or a trained volunteer/intern. Scoring consisted of recording a point value corresponding to a stage of soft tissue decomposition. Stage of decomposition is assessed by visually examining gross morphological changes. The body is assessed in three areas; the head and neck, the torso, and the limbs. A complete list of the categories associated with each body segment is provided in Table 3. Scores were taken independently; the morning score was not used to influence or determine the afternoon score, nor was the preceding day's score considered when determining the following day. This allowed for scores to be based solely on the visual observations at the specific time of data collection. Categories and descriptions were not altered for the animal remains; all characteristics were

Table 3: Scoring categories and points for each body segment. From Megyesi et al., 2005.

Categories and Corresponding Descriptions for Scoring the Head & Neck		Assigned Score
A. Fresh		
1. Fresh, no discoloration.		1 pt
B. Early Decomposition		
1. Pink-White appearance with skin slippage and some hair loss.		2 pts
2. Gray to green discoloration; some flesh still relatively fresh.		3 pts
3. Discoloration and /or brownish shades particularly at edges, drying of nose, ears, and lips.		4 pts
4. Purging of decompositional fluids out of eyes, ears, nose, mouth, some bloating of neck and face may be present.		5 pts
5. Brown to black discoloration of flesh.		6 pts
C. Advanced decomposition		
1. Caving in of the flesh and tissues of eyes and throat.		7 pts
2. Moist decomposition with bone exposure less than one half that of the area being scored.		8 pts
3. Mummification with bone exposure less than one half that of the area being scored.		9 pts
D. Skeletonization		
1. Bone exposure of more than half of the area being scored with greasy substances and decomposed tissue.		10 pts
2. Bone exposure of more than half of the area being scored with desiccated or mummified tissue.		11 pts
3. Bones largely dry, but retaining some grease.		12 pts
4. Dry bone.		13 pts
Categories and Corresponding Descriptions for Scoring the Trunk		Assigned Score
A. Fresh		
1. Fresh, no discoloration.		1 pt
B. Early Decomposition		
1. Pink-white appearance with skin slippage and marbling present.		2 pts
2. Gray to green discoloration; some flesh still relatively fresh.		3 pts
3. Bloating with green discoloration and purging of decompositional fluids.		4 pts
4. Postbloating following release of the abdominal gases, with discoloration changing from green to black.		5 pts
C. Advanced Decomposition		
1. Decomposition of tissue producing sagging of flesh; caving in of the abdominal cavity		6 pts
2. Moist decomposition with bone exposure less than one half that of the area being scored.		7 pts
3. Mummification with bone exposure less than one half that of the area being scored.		8 pts
D. Skeletonization		
1. Bones with decomposed tissue, sometimes with body fluids and grease still present.		9 pts
2. Bones with desiccated or mummified tissue covering less than one half of the area being scored.		10 pts
3. Bones largely dry, but retaining some grease.		11 pts
4. Dry bone.		12 pts
Categories and Corresponding Descriptions for Scoring the Limbs		Assigned Score
A. Fresh		
1. Fresh, no discoloration.		1 pt
B. Early Decomposition		
1. Pink-white appearance with skin slippage and marbling present.		2 pts
2. Gray to green discoloration; some flesh still relatively fresh.		3 pts
3. Bloating with green discoloration and purging of decompositional fluids.		4 pts
4. Postbloating following release of the abdominal gases, with discoloration changing from green to black.		5 pts
C. Advanced Decomposition		
1. Decomposition of tissue producing sagging of flesh; caving in of the abdominal cavity		6 pts
2. Moist decomposition with bone exposure less than one half that of the area being scored.		7 pts
3. Mummification with bone exposure less than one half that of the area being scored.		8 pts
D. Skeletonization		
1. Bones with decomposed tissue, sometimes with body fluids and grease still present.		9 pts
2. Bones with desiccated or mummified tissue covering less than one half of the area being scored.		10 pts
3. Bones largely dry, but retaining some grease.		11 pts
4. Dry bone.		12 pts

considered in the same manner for all species.

Insect collection

In order to assess taxonomic variation between subjects by species, adult flies were collected from the pig and human remains using a standard net. Flies were netted while on the body and when flying above the remains. Adult flies are useful in addressing species variation because adults are frequently identifiable to the species level by examining morphological characteristics alone (Amendt et al., 2004). Beetles were collected using forceps. Flies and beetles were placed directly into a 70% ethanol solution for storage and later identification.

Fly larvae were collected and killed either using a kerosene, acetic acid and ethanol (KAA) mixture, or by boiling water. Larvae were collected from all masses observed on the remains, and an attempt was made to collect at a representative mix of sizes of larvae. This was done to capture the full spectrum of variation present at a given time. The different masses may have contained different larval species and the various sizes of maggots present indicated larvae in a multitude of developmental stages. Examining the developmental stages aids in determining timing of succession (Gruner et al., 2007). Although timing of succession is not analyzed in this dissertation, it may be an avenue of possible future research and so the data were collected. The larvae were then stored in a 70% ethanol solution for long-term preservation (Amendt et al., 2007). When maggot masses were visible on the remains, the temperature of the mass was measured using an infrared thermometer gun. Large maggot masses can generate significant amounts of heat, which in turn can increase the rate of decomposition progression (Catts and Goff, 1992). If noticeable differences in temperature were detected between human and pig remains due to maggot activity, it could help explain possible differences in TBS. First appearance of maggot activity were noted in the daily data collection logs, and photographs of all maggot masses were taken.

Other insects such as wasps, ants, and bees were noted during observation, but were not captured for further preservation. This was done following the advice of the consulting entomologist, Dr. Ralph Williams. Wasps, ants, and bees do not typically contribute to the decomposition of humans or pigs and are not considered forensically significant species.

Data analysis

Insect taxonomic identification

Adult flies were identified to the genus or species level following the taxonomic keys in the *Manual of Nearctic Diptera* (McAlpine et al., 1981). These keys include species from a wide geographic area, and are the standard type of keys used in entomological identification (Dominguez, 2007). Fly larvae were identified to family level following similar taxonomic keys. Use of these keys requires examination of visible external features. The keys function in a hierarchical fashion; the most common features are used to identify family, then more precise variants of features on the wings or thorax are used to identify to genus, and then further distinctive features can be used to determine species. Morphological indicators only were used to identify specimens; no DNA analysis was conducted. Over 2000 larval specimens were collected throughout the three trials. A random sample of 300 larvae (15% of the total sample) were identified for the analysis discussed here. Random samples were selected by a randomization procedure in SAS 9.4. All three trials are represented in the analyzed samples. This strategy allowed for testing the hypothesis of taxonomic difference between carrion species by providing what should be a representative sample of the insect variation present on human and pig remains. A random sample was analyzed as opposed to every specimen collected due to time constraints.

Insect activity patterns

In addition to identifying the type of insect prevalent on the pig and human samples, a pattern analysis of insect activity was also conducted. The first sighting of fly activity was noted

for each individual, as well as the first appearance of maggot activity. The number of maggot masses was also recorded to differentiate between localized larval activity and widespread (covering the majority or entire body) maggot movement.

Scavenging

Scavenging activity was analyzed for all three trials. Photographs from the game cameras along with daily observation notes were reviewed to determine the total number of scavenger species present in each trial. Within each trial, the first instance of scavenging on each subject was recorded, along with the total number of scavenging events. These analyses were completed by Steadman et. al (2016) for presentation at the 2016 American Association of Forensic Sciences meeting. Daily and weekly counts of scavenging activity were also tabulated.

Scavenging was determined to have occurred when visual examination of the pig or human remains, either in person or via photograph or game camera image, showed damage to the remains that had not been seen during the previous observation period. Damage included scratches, tissue disruption such as open wounds, punctures in the skin or extraction of muscle tissue or organs.

Statistical analyses

Hierarchical linear modeling (HLM)

One primary research question explored in this dissertation is “are pigs and humans similar in their decomposition pattern?” In addition to visual examination, hierarchical linear modeling (HLM) was used to quantify if and how the decomposition patterns differed between the two species. Average weekly body segment scores, from the TBS system, were evaluated and scavenging was incorporated into the model.

Hierarchical linear modeling is a form of ordinary least squares regression that is capable of handling hierarchical or nested data. Data are nested when repeated measurements are taken

from the same subjects over a period, as was done here with the twice-daily TBS. Ordinary least squares regression is a type of analysis that explores the causes of variation in a relationship between variables. For these analyses, the level one variable (the level at which the measurement is taken) is body segment score, and the level two variable (the larger category within which the level one variable is nested) is species. HLM allows for covariates at each level, such that a generalized equation for a two-level model could be written as

$$Y_{ijk} = \lambda_{00} + \lambda_{10}X_{ijk} + \beta_{01j}X_{jk} + \beta_{11j}X_{ijk}X_{jk} + \gamma_{0jk} + \gamma_{1jk}X_{ijk} + e_{ijk}$$

where λ_{00} is the overall intercept, $\lambda_{10}X_{ijk}$ is the level one covariate, $\beta_{01j}X_{jk}$ is the level two covariate, $\beta_{11j}X_{ijk}X_{jk}$ is the interaction effect of the covariates, γ_{0jk} is a level one random effect, $\gamma_{1jk}X_{ijk}$ is a level two random effect, and e_{ijk} is a residual error term (Ene et al., 2008).

Covariates that can affect body segment scores are time (as measured in weeks), temperature (measured in degrees Celsius), and scavenging (measured in number of times scavengers damaged tissue), and these were included as fixed or random effects. Variables were modeled as fixed effects if they were likely to change the same way across species (example: time) and random if not (example: scavenging). HLM was chosen here because it does not require that each observation be completely independent of the others, which is critical in any data set that changes over time. Here, the lack of independence again refers to the fact that the TBS were recorded from the same individuals throughout each trial. As decomposition is a progressive process, each day's scores were at least in part influenced by the previous day's activity. This is also why time, in weeks, was evaluated as a potentially significant driver of variation. HLM can also model non-linear and discontinuous change across time (Statistics solutions, 2017). As discussed in the literature review, decomposition is a complex and complicated process, and its progression does not always proceed in a linear manner. This could manifest as scores that are

lower than the previous day's, or scores that remain constant for a few observations before jumping noticeably. HLM has other advantages, most notably that it is capable of detecting cross-level interactions, meaning that relationships between variables at level one (here, TBS and time) and variables at level two (here, species and temperature) can be identified. In addition, HLM is equipped to handle repeated measures data, small sample sizes, and heterogeneity of variance across repeated measures (Woltman et al., 2012). Disadvantages to HLM include that it is more complex to calculate than OLS, and requires more processing time. In addition, larger sample sizes are needed for strong power, although this can be tempered by having more groups as opposed to many observations within each group. Another disadvantage is that HLM does not handle missing data well (Woltman et al., 2012).

Assumptions of HLM include normality of the data as well as equal variances of the groups. Averaging the segment scores by species and then by week provided the normal distribution necessary, as well as allowed the data to be treated as continuous. Scores were first averaged by species because the main question is whether pigs and humans as species on average display different decomposition patterns. Segment scores were evaluated as opposed to TBS because it was of particular interest to understand if specific areas of the body decomposed significantly differently than others. This also made biological sense; the weight distribution in pigs is centered in the head and neck and trunk, while the limbs are quite small. In humans, weight is more evenly distributed across segments.

The results of this analysis will inform if a particular body segment drives the variation in decomposition patterns between pigs and humans. The HLM analyses will also help to address the hypothesis that raccoons will be more likely to scavenge the humans, specifically on the limbs. If supported, then the HLM should show significant differences between the species on

for the limb segment in particular. Scavenging (in counts of times that scavengers were recorded disturbing the remains) is also entered as an independent variable to help identify if scavenging activity in general leads to significant differences in segment score regardless of which body segment is impacted.

Time series (dynamic linear regression)

As discussed in Chapter 2, decomposition is a complicated and complex process influenced by multiple factors that interact with each other. While the HLM analyses examines whether or not pigs and humans have similarities in their decomposition patterns, it cannot address the question of the accuracy of TBS (and by extension PMI) prediction of using an animal model as a direct substitute for human remains. If forecasts derived from pig data are inaccurate, the HLM might help to explain why and how the pig model diverges from human patterns. Predictive modeling is better suited to the question of accuracy of TBS/PMI determination because it allows for comparison between predicted or forecasted values based on pig data to be compared to actual values from human data. As decomposition is a time directed process, any predictive model must incorporate a change over time as part of the equation.

As discussed in the review of non-linear systems theory, time series statistical methods include both the change over time component and the predictive or forecasting ability, and are therefore ideal methods for examining chaotic systems. All time series models incorporate information from past observations of a series, but not all time series techniques allow for the inclusion of other information from key factors (Hyndman and Athanasopoulos, 2014). In the analyses discussed here, insect activity and scavenging were considered key factors whose effects needed to be incorporated into the models. Dynamic linear regression, a specific type of time series analysis, was used to build the models, and the presence or absence of insects and the

amount of scavenging were included as dynamic regressors. A generalized equation of a dynamic linear regression can be written as

$$Y'_t = b_1 X'_{1,t} + b_2 X'_{2,t} + b_3 X'_{3,t} + N'_t$$

where the first three terms represent the variable coefficients, and N'_t is the regression error (Makridakis et al., 1998).

Six models of decomposition progression were constructed using SAS version 9.4 and R version 3.4.1; one model was built for the pigs and one for the humans in each of the three trials. The trials were separated because each trial used unique human and pig subjects. Daily TBS was the dependent variable, and daily average temperature, average daily amount of scavenging, and presence or absence of insect activity were the predictor variables. Scavenging was counted by reviewing game camera and Nikon photographs and recording an “event” each time scavengers were present and corresponding changes to the soft or hard tissue of the remains was documented. Time was measured as day of the week and week of the month; this means that each model had two seasonal components to capture the variation in the span of a week and within a month. This distinction is important because for spring and winter, it generally takes longer to show any noticeable decomposition progression, so capturing the variation within a month (weekly) will be necessary to elucidate the patterns. For summer, decomposition can progress so quickly that daily variation is just as important as weekly variation to understanding progression and pattern differences. TBS was averaged for the pigs and for the humans separately. Using the average allows for a more continuous distribution as well as helps to eliminate white noise and the effects of outliers in the model development. Again, the primary focus for these analyses was on species differentiation.

Autocorrelation functions (ACF) and partial autocorrelation functions (PACF) were

examined using ACF and PACF plots called correlograms to determine if there was a relationship between one observation and the next, or if the previous observation had little impact. These plots are also useful in determining if seasonality, trend and cyclical patterns exist within the data (Makridakis et al., 1998). The relationship between the data points as well as features like seasonality, trend, and cyclicity needs to be evaluated when building the models to determine if these components should be included in the time series equations. The most successful models are those that capture the pattern of the data series being analyzed without using overly complicated equations. Therefore, tests such as the ACF and PACF are useful for ensuring that the models do not include extraneous components.

All six models were evaluated using several goodness of fit statistics. Mean absolute percentage error (MAPE) was the primary indicator of a strong model. MAPE is calculated according to the formula

$$\Sigma(\% \text{ difference [actual to predicted]}/n)$$

which can be explained as the sum of the percent of difference of the predicted observation from the actual observation divided by the number of observations.

The lower the MAPE, the better the model was able to reproduce the pattern observed in the data. The data were divided into a training sample (n= 70 days for Trial 1 Spring, n= 31 days for Trial 2 Summer, and n=105 days for Trial 3 Winter), which was used to develop the model, and a holdout sample (n=7 for Trial 1 Spring, n=4 for Trial 2 Summer, n=7 for Trial 3 Winter), which was used to test the model.

Spearman's ranked correlation coefficient was used to compare the forecasted pig values to the actual human values for each trial. This statistic was chosen because it is non-parametric and does not require normality of the residuals. Spearman's correlation measures the linear

interdependence of two variables; therefore it is critical that there is a linear relationship between the two sets of data. The forecasted pig values were also compared to the actual human values to determine if such a linear relationship actually existed in order to determine the validity of the Spearman's correlation coefficient. Spearman's ranked correlation coefficient is calculated as

$$R = 1 - [6\sum d_i^2 / n(n^2 - 1)]$$

where d is the difference between the ranks on corresponding rows of a data table. The value of the correlation coefficient can be positive or negative, and will always range from -1 to 1 (Laerd Statistics, 2013).

A large amount of data was collected during this project. Results are presented in three chapters; one for the insect activity patterns, one for the scavenging patterns, and one chapter for the statistical analyses. Photographs from the game cameras and the Nikon camera are incorporated into the first two results chapters, while the bulk of the numerical data are presented in the third results chapter.

Chapter VI. Insect Results

This chapter presents the results of the insect species and activity pattern analysis. The discussion of species identification is limited to adult fly specimens only. The larvae were analyzed to family level. Although adult beetles were collected as well, there were insufficient numbers from each trial to justify identifying by species and attempting to determine succession patterns. The results are presented by trial as the insects from each trial were observed and collected independently. Also, as discussed in Chapter 3, different fly species are frequently present during different seasons, so it is logical to organize their discussion chronologically.

Adult flies were identified to the species level to address the hypothesis that insect type would not vary significantly between the pig and human individuals. Previous studies comparing humans and pigs (e.g. Schoenly et al., 2007) have documented that there are no significant differences in fly type attracted to various species of carrion in the same local environment. Adult flies were used for identification to species level because adults can be identified through visual inspection of morphological traits and do not require live storage for rearing to adulthood or the use of DNA analysis as larvae do.

Insect species identification

Adult flies were collected during Trials 1 and 2. No insect activity occurred during Trial 3 Winter. Table 4 summarizes the species noted during Trials 1 and 2. Similar species were observed on the pigs and the humans; most were of the *Calliphoridae* family. House flies (*Muscidae sp.*) were only noted on the pigs, while flesh flies (*Sarcophagidae*) were only seen on the human donors. It should be noted however, that the author is not a professional entomologist, and the captured and analyzed specimens likely do not represent the full complement of species that were present. No major adult fly species differences were noted between the pigs and humans, which is consistent with previous research conducted at the ARF. In both Trials 1 and 2,

Table 4: Adult flies identified from Trials 1 and 2.

Trial 1 Spring Human	Trial 1 Spring Pig	Trial 2 Summer Human	Trial 2 Summer Pig
<i>Lucilia silvarum</i>	<i>Lucilia silvarum</i>	<i>Lucilia silvarum</i>	<i>Lucilia silvarum</i>
<i>Lucilia coeruleiviridis</i>	<i>Calliphora vomitoria</i>	<i>Calliphora vomitoria</i>	
<i>Sarcophagidae</i>	<i>Muscidae sp.</i>	<i>Lucilia coeruleiviridis</i>	<i>Lucilia coeruleiviridis</i>
<i>Phormia regina</i>		<i>Phormia regina</i>	<i>Phormia regina</i>

there was slightly more species diversity observed on the human remains as compared to the pigs. Four species were collected from the humans, while only three were identified from the pig remains. Schoenly et al. (2007) also documented marginally higher rates of species diversity when comparing humans to pigs at the ARF.

Larvae were only identified to family level; of the larvae sampled, all were from the *Calliphoridae* family. This is correlated with the adult fly identification, as most of the adult flies were also Calliphorids. No larvae were kept and reared to adulthood for more precise identification. As the larvae were all from the same family regardless of whether they were collected from the humans or the pigs, there are no distinguishable patterns that can be identified from these data. The bulk of the results of this chapter, therefore, are concentrated on the observable patterns of fly and larva activity.

Insect activity patterns

Activity patterns were tracked by dates of oviposition, date of first larval activity, location of first larval mass, and last date of insect activity. Last date of insect activity corresponds to the last day that any larvae or adult flies were observed on the remains. Duration of insect activity was then calculated based on first and last observations. The first larval mass was designated based on the first observation of multiple larvae on a specimen; to distinguish between the first few larvae and the first active mass that could impact TBS and rate of

decomposition the larvae had to survive for at least 24 hours. This meant that in Trial 1 Spring, there were occasionally a few larvae that were observed earlier than the first mass was counted. Insect activity patterns are summarized in Table 5. Note that in the first trial, all of the humans first had larval masses in the facial area, while the first location of larval mass for the pigs was much more diverse and included everything from head to tail.

Table 5: Insect activity patterns based on dates and anatomical locations for all subjects by trial.

Trial	Subject	Species	Date of 1 st oviposition	Date of 1 st larval activity and TBS	Location of 1 st larval mass	Date of last insect activity and TBS	Duration of larval activity
1	116-13	H	3/19/14	3/23/14, TBS=9	mouth	5/11/14, TBS=22	50 days
	115-13	H	3/16/14	3/26/14, TBS=10	mouth	5/14/14, TBS=20	50 days
	113-13	H	3/19/14	3/27/14, TBS=11	nose	5/14/14, TBS=23	49 days
	114-13	H	3/17/14	3/27/14, TBS=11	mouth	5/18/14, TBS=22	53 days
	112-13	H	3/17/14	3/27/14, TBS=13	eyes	5/11/14, TBS=20	46 days
	107-13	P	3/17/14	3/27/14, TBS=10	axilla	5/11/14, TBS=18	46 days
	108-13	P	3/16/14	3/26/14, TBS=10	anus	5/10/14, TBS=18	46 days
	109-13	P	3/19/14	3/26/14, TBS=10	anus	5/7/14, TBS=18	43 days
	110-13	P	3/18/14	3/25/14, TBS=10	mouth	5/9/14, TBS=26	46 days
	111-13	P	3/19/14	3/25/14, TBS=10	mouth	5/14/14, TBS=22	51 days
2	117-13	H	6/14/14	6/14/14, TBS=3	nose	7/1/14, TBS=24	18 days
	118-13	H	6/14/14	6/15/14, TBS=5	nose	7/3/14, TBS=25	19 days
	119-13	H	6/14/14	6/15/14, TBS=3	mouth	6/25/14, TBS=21	11 days
	120-13	H	6/14/14	6/14/14, TBS=4	nose	6/27/14, TBS=22	14 days
	121-13	H	6/14/14	6/14/14, TBS=3.5	mouth	6/25/14, TBS=23	12 days
	122-13	P	6/13/14	6/13/14, TBS=3	snout	6/28/14, TBS=30	16 days
	123-13	P	6/13/14	6/13/14, TBS=3	snout	6/28/14, TBS=28	16 days
	124-13	P	6/13/14	6/13/14, TBS=3	mouth	6/28/14, TBS=30	16 days
	125-13	P	6/13/14	6/13/14, TBS=3	mouth	6/28/14, TBS=27	16 days
	126-13	P	6/13/14	6/13/14, TBS=3	eyes	6/28/14, TBS=30	16 days

Trial 1 spring

(March 14-May 27, 2014; low temperature 2.6 degrees Celsius, high temperature 24.2 degrees Celsius, average temperature 16.2 degrees Celsius)

Blowflies appeared on both the pig and human subjects soon after placement.

Temperatures prevented larval growth for the majority of the subjects for the first three weeks after deposition. When oviposition and subsequent larval development did occur, the locations differed between the two species. In the humans, flies most frequently oviposited in areas that had been scavenged in addition to the orifices. In pigs, the majority of the eggs and larvae were seen at the ground-body interface, and adhering externally to the coarse body hair. Figures 4 to 6

present the images chronologically. In Figure 4, flies can be observed on the face of one of the humans. This was seen on all of the humans; note the corresponding location of the egg masses or larval activity in each photograph. Most of the fly eggs on the pigs did not hatch; their external placement left them more vulnerable to the fluctuating cold temperatures. In contrast, several of the human subjects had larval activity in the mouth or nose as early as 12 days into the trial, while none of the pigs showed significant larval activity until 35 days after placement when ambient temperatures increased.



Figure 4: Trial 1 Spring, 114-13R with fly activity on face. Day 7.



Figure 5: Trial 1 Spring, 116-13R with larval activity in the mouth. Day 12.



Figure 6: Trial 1 Spring, 111-13R with egg masses on chin. Day 21.

At 35 days after placement, all human and pig subjects displayed active larvae (Figures 7 through 16). Higher ambient temperatures during the day allowed more larvae to hatch and aid in the decomposition process. The locations of these larvae corresponded to the oviposition locations noted earlier. Raccoons had scavenged only human subjects during Trial 1 Spring (as shown in Figure 7), and so only human subjects showed larval masses in areas other than the natural orifices or the ground-body interface. This larval activity led to greater bone exposure in the humans, which corresponded to higher total body scores. Due to the earlier presence of larvae in the body cavities of the humans, the TBS were already higher by the time the ambient temperatures increased. Figures 8 and 9 compare a pig and human on the same day, and the visible difference in decomposition progression is striking. Compare also Figures 11 and 13 with Figure 16. The larvae in the facial orifices in the pigs depicted in Figures 11 and 13 are small, with masses are fairly constrained. The larvae in the facial orifices of the human in Figure 16 are larger, and the masses are clearly greater in volume. This indicates that even when located in a similar place, there is still a difference in the larval activity between the humans and the pigs.

Figures 17 through 19 were all taken at 38 days after placement, approximately half way through the trial period. As temperatures continued to rise, more external larval activity was observed on all subjects. Insect activity patterns continued in the same manner until the completion of data collection for Trial 1 Spring. As seen in Figure 17, larvae were able to move under the epidermal layer of skin on the humans, but not on the pigs. This led to more widespread insect activity on the surface of the humans, while the bulk of the larval activity on the pigs was along the ground-body interface. The difference in location was important for two reasons; the first was that the larval activity on the humans was more likely to lead to advanced decomposition and/or bone exposure in a visible area and thus lead to a higher TBS.



Figure 7: Trial 1 Spring, 112-13R (human subject) with larval activity in the right foot in an area opened by raccoon scavenging. Day 35.



Figure 8: Trial 1 Spring, 113-13R with larval activity moving from face to neck and chest. Day 35.



Figure 9: Trial 1 Spring, 107-13 R with larval activity on exterior near mouth and along ground-body interface (see arrow). Day 35.



Figure 10: Trial 1 Spring, 107-13R with larvae on the exterior hind leg. Day 35.



Figure 11: Trial 1 Spring, 108-13R with fly activity on exterior head. Day 35.



Figure 12: Trial 1 Spring, 108-13R with larval activity on hind leg. Day 35.



Figure 13: Trial 1 Spring, 110-13R with larval activity in mouth and eye. Day 35.

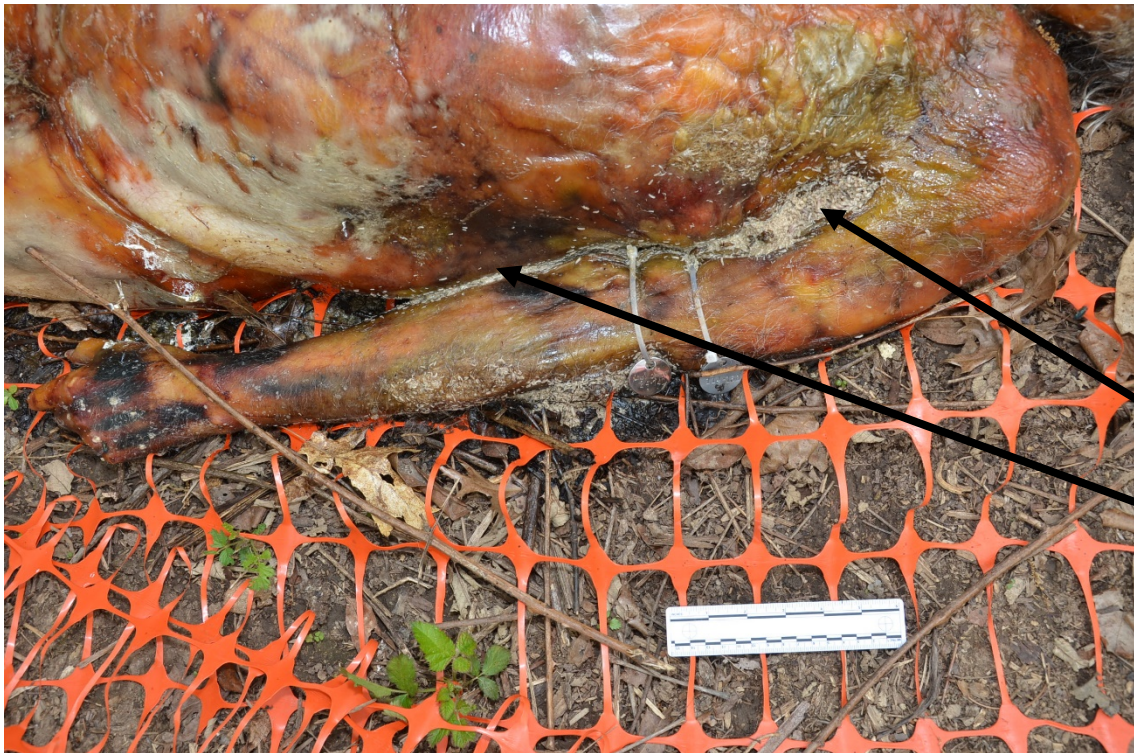


Figure 14: Trial 1 Spring, 114-13R with larval activity in axilla and underneath body (see arrows). Day 35.



Figure 15: Trial 1 Spring, human 112-13 R with larval activity in opening in leg. Day 35.



Figure 16: Trial 1 Spring, 112-13R with larval activity in facial orifices. Day 35.



Figure 17: Trial 1 Spring, human 114-13R with larval activity under the epidermal layer of skin on the right leg (see arrow). Day 38



Figure 18: Trial 1 Spring, 107-13R with continued larval activity at the ground-body interface. Day 38.



Figure 19: Trial 1 Spring, 112-13R with larval activity protruding out of the facial orifices. Day 38.

Secondly, the larvae moving on the surface of the human remains attracted more birds and other insectivorous scavengers. This again frequently led to more advanced decomposition compared to the pigs. This connection between insects, scavengers, and TBS is also a reminder of the multiple variables and interaction effects in the decomposition sequence. Again, this is why decomposition must be assessed as a complicated and complex process and not merely the sum of its respective parts.

Trial 2 summer

(June 13-July 17, 2014, low temperature 19.5 degrees Celsius, high temperature 28.7 degrees Celsius, average temperature 24.2 degrees Celsius).

Insect activity during the second trial was much more consistent than during Trial 1 Spring. Trial 2 Summer ran from June 13, 2014- July 31, 2014 and temperatures remained high the entire time. Oviposition was seen as early as a few hours after placement on the snout of

some of the pigs (Figure 20) and oviposition was observed on all subjects within 24 hours after placement.

Similar to Trial 1 Spring, much of the oviposition on the pigs was observed externally as opposed to just in the orifices, as was seen on the humans. Figures 20 and 21 depict the typical oviposition pattern observed on the heads of the pigs and humans. Note that the egg masses are much larger on the head of the pig. This led to large larval masses on the head of the pigs, which later joined with larval masses from other areas of the body.

Larval activity was observed on the pigs and humans within 3 days after placement. Small larvae were present on the head and neck of both species, as seen in Figures 22 and 23. These figures also document how much more widespread the larval activity was on the heads of the pigs compared to the humans.



Figure 20: Trial 2 Summer, Fly eggs on snout of 122-13R. Day 0.



Figure 21: Trial 2 Summer, 119-13R with fly activity and egg masses in nostril. Day 1.



Figure 22: Trial 2 Summer, 118-13R with larval activity protruding from nostril onto upper lip. Day 2.



Figure 23: Trial 2 Summer, 123-13R with larval activity on snout. Day 3.

Examining Figures 23 and 24 together shows how quickly (2 days) the larvae were able to consume enough soft tissue for the bulk of the pig's head to skeletonize.

In humans, maggot activity began in the facial orifices and scavenging sites before spreading to other areas of the body. In pigs, maggot masses began in the snout and anus and the two masses eventually spread to cover the entire body. An example of the typical pig pattern can be seen in Figure 23, while Figures 25 and 26 documents the pattern observed on the humans. Pigs skeletonized more quickly than humans during Trial 2 Summer in part due to this difference in spread of maggot masses. In addition to consuming the soft tissue, maggot masses generate a significant amount of heat, which can speed up decomposition processes.



Figure 24: Trial 2 Summer, 123-13R with maggot masses from head and rear joining to encompass entire body. Day 5. Note the dramatic change from Figure 20, which was only two days prior.



Figure 25: Trial 2 Summer, 118-13R with larval activity in eyes and right arm at scavenging opening. Day 4.



Figure 26: Trial 2 Summer, Close up of 118-13R larval activity in opening in right arm made by raccoon scavengers. Day 4. Note that the larvae are contained within the scavenging site and not joining up with other masses as observed on the pigs.

Summary

Insect activity plays an important role in determining the rate of decomposition. While the species type may not have differed significantly between the pigs and humans, the locality of oviposition and the resulting larval masses did. This in turn contributed to a sometimes dramatic difference in segment and total body scores. These scores will be addressed more thoroughly in Chapter 8 in the statistical analysis section. Another source of variation in the decomposition patterns between the pigs and humans was seen in the behavior of scavengers, which is the topic of the next chapter.

Chapter VII. Scavenging Results

In each trial there was evidence of scavenging activity on at least one of the individuals. For Trials 1 and 2, the scavenging was limited to the human subjects. In Trial 3 Winter, during the height of winter, scavenging was observed on all of the human subjects and eventually all of the pigs. Scavenger type varied by trial. For Trials 1 and 2, raccoons (*Procyon lotor*) and opossum (*Didelphis virginiana*) were most frequently observed and were the only animals to directly scavenge the remains. A variety of small bird species was also observed on the remains, but it was unclear from the game camera photos if they were feeding on the insects or on the remains directly. Game camera images clearly showed raccoons scavenging muscle tissue from human remains during the first two trials. opossums consistently appeared after the raccoons and used the same feeding sites. This led to the question of whether or not the opossums were scavenging the remains or consuming the insect larvae that colonized the openings made by the raccoons. It is most likely that the opossums were consuming tissue as they are well documented to feed on carrion (DeVault et al., 2004).

Trial 3 Winter presented a unique situation as there were very few insects present, and the few flies observed were not active until the very end of the sample period. The cold temperatures precluded any insect activity, and seemed to correlate with a noticeable increase of scavenging of the remains of both the human and pig subjects. A greater number of raccoons was observed during the third trial, along with opossums and at least one skunk (*Mephitis mephitis*). No insects were present, which also confirmed the opossums and skunks consumed tissue and not just fly larvae. Table 6 shows the scavenger type and number of scavenging incidents for each trial. Scavenging incidents were tabulated using the game camera and daily photos to count unique appearances of a scavenger, supported by corresponding damage to a pig or human subject. The

Table 6: Scavenger type and minimum number of scavenging events by trial.

Scavenger Type	Trial 1 Spring	Trial 2 Summer	Trial 3 Winter
Raccoon	15	22	190
Opossum	13	19	100
Skunk	0	0	2
Bird (various)	Present	Present	Present

numbers presented below are a minimum number of events. Raccoons in particular were often observed in game camera photos returning to the same location multiple times in one night and it was not possible to distinguish each event. If multiple animals were observed in a game camera photograph then each animal was counted as making one unique appearance. Only mammalian scavenging incidents were counted; birds were noted as being present or absent, and birds were not identified by type.

Patterns of scavenging also differed between pigs and humans in terms of body locations affected. Table 7 shows the individuals that were scavenged and which body segment was impacted first. The body segments are designated using the same terminology as the TBS system. It is important to track how the segments were scavenged because the bone exposure caused by the scavenging event frequently caused the segment score to be higher for that area. The table clearly shows that the limbs were preferentially scavenged in the humans, comprising the first segment to be affected for eight out of the ten humans. For the five pigs, the most common starting segment was the head and neck, followed by the trunk. The total number of body areas scavenged refers to more specific anatomical features such as the forearms, hands, feet, or nose. Comparing the total number of body areas affected shows a distinct preference again for the humans compared to the pigs. It also demonstrates that among the pigs in Trial 3

Table 7: Body segment locations and counts of anatomical features scavenged by trial. Note that no pigs were scavenged during Trials 1 and 2.

Trial	Subject	Species	Body Segment Scavenged (first to last)	Total number of body areas scavenged
1	114-13R	H	Limbs	2
	112-13R	H	Limbs	10
2	117-13R	H	Limbs	6
	118-13R	H	Limbs	4
	121-13R	H	Limbs	7
3	145-13R	H	Limbs, Trunk, Head and Neck	27
	142-13R	H	Limbs, Head and Neck, Trunk	18
	143-13R	H	Limbs, Head and Neck, Trunk	9
	144-13R	H	Head and Neck, Trunk, Limbs	19
	146-13R	H	Trunk, Limbs, Head and Neck	8
	133-13R	P	Head and Neck, Trunk, Limbs	8
	132-13R	P	Trunk, Limbs	3
	134-13R	P	Head and Neck, Trunk, Limbs	11
	136-13R	P	Limbs, Head and Neck, Trunk	6
	135-13R	P	Trunk, Limbs	4

Winter, there was one pig that was scavenged more heavily than the others, although the preference was not as distinct as the preference of the raccoons for a specific human donor.

Trial 1 spring

The following images (Figures 27 through 36) were captured by the Moultrie game cameras placed along the transect. During the first trial, scavenging activity was limited to two humans, 112-13R and 113-13R. Raccoons and opossums repeatedly scavenged the limbs and feet of 112-13R. Scavenging on 113-13R was limited to the feet and occurred only at the end of the sampling period. It is important to note the differences in behavior between the two scavenger types. The raccoons were responsible for the primary destruction of tissue. Raccoons scratched or clawed openings into the limbs or feet to extract muscle tissue. The following photographs document the raccoons first damaging the remains and then show the opossums accessing the same sites as the raccons. In this trial, it is unclear if the opossums are consuming the remains or if they are strictly consuming the fly larvae that infested the scavenging sites. It is



Figure 27: Raccoon scavenging the left arm of human 112-13R.



Figure 28: Opossum scavenging left arm of human 112-13R after raccoon has created opening.



Figure 29: Raccoon returning to original scavenging site of human 112-13R.



Figure 30: Raccoon scavenging left leg of human 112-13R.



Figure 31: Raccoon expanding on scavenging site of left leg of human 112-13R.



Figure 32: Opossum returning to original scavenging site on left arm of human 112-13R; possibly consuming fly larvae.



Figure 33: Raccoon removing muscle tissue from the left leg of human 112-13R.



Figure 34: Opossum eating larvae from near human 112-13R.



Figure 35: Raccoon opening foot of human 112-13R.



Figure 36: Opossum accessing same scavenging site as raccoon on human 112-13R.

also important to note that the raccoons preferentially scavenged the humans; the two humans that were scavenged in this trial were returned to repeatedly, despite having open access to the other donors and the pigs. This indicates that there is some other motivation for the preferential behavior. Also somewhat unusual was the consistent daytime scavenging. While raccoons tend to be nocturnal, they were often photographed by the game cameras accessing the human donors during both the morning and afternoon hours (Smith, 2015).

Trial 2 summer

During the second trial raccoons again scavenged the humans preferentially to the pigs. Four of the five human subjects were scavenged, while none of the pigs showed any signs of scavenging damage, nor was any activity captured on the game cameras. Scavenging of the humans was limited to the limbs. Similar to the first trial, one of the humans was the preferred scavenging target, and the raccoons returned to this particular individual multiple times. During the first trial, only one raccoon at a time scavenged the remains. Trial 2 Summer showed groups of raccoons scavenging the same individual simultaneously. Opossums were active during this trial, following the raccoon activity in the same manner as observed during Trial 1 Spring. Figures 37 through 47 document this pattern.



Figure 37: Multiple raccoons ($n=3$) examining the placement area of Trial 2 Summer.



Figure 38: Opossum in the placement area of Trial 2 Summer.



Figure 39: Raccoon approaching human 119-13R.



Figure 40: Opossum near human 119-13R.



Figure 41: Group of raccoons (n=4) scavenging human 119-13R.



Figure 42: Raccoon scratching left shoulder of human 117-13R.



Figure 43: Raccoon removing tissue on left shoulder of human 117-13R.



Figure 44: Maggot mass in left shoulder of human 117-13R where raccoon scavenging occurred.



Figure 45: Raccoon scavenging right shoulder of human 117-13R after the left shoulder was scavenged earlier. This demonstrates the proclivity of the raccoons to preferentially scavenge certain individuals.



Figure 46: Opossum using raccoon scavenging site on right shoulder of human 117-13R.



Figure 47: Multiple raccoons scavenging right side of human 117-13R.

Trial 3 winter

Trial 3 Winter had the most unique scavenging pattern of any trial. The temperatures were much lower than during the previous two trials, and there was no discernable insect activity until the end of the sampling period. Scavenging was much heavier during this trial; all of the pigs and all of the humans showed some evidence of scavenging (Figures 48 through 61). Similar to previous trials, the raccoons displayed a distinct preference for one of the humans compared to the others; the humans were also more extensively scavenged than the pigs. As seen in Figures 50 and 57, opossums again followed the raccoons and took advantage of the access to the remains provided by the raccoons. Groups of raccoons were again observed visiting the same set of remains simultaneously. Juvenile raccoons were also seen during this trial, feeding on remains and exploring the placement area. Juvenile raccoons were not observed as frequently feeding on the remains, but instead appeared to be using the research area as a playground, pulling on cages and using the data loggers as toys. Trial 3 Winter was also unique in that it



Figure 48: Skunk on top of human 143-13R. Tissue damage to 143-13R observed the following day suggests that the skunk fed on the remains.



Figure 49: Raccoon scavenging pig 134-13R.



Figure 50: Opossum scavenging pig 134-13



Figure 51: Skunk scavenging pig 134-13R. The skunk is at the back of the pig, and only the tail of the skunk is visible. See arrow.



Figure 52: Raccoon returning to scavenge pig 134-13R despite snow.



Figure 53: Skunk returning to pig 134-13R during snow.



Figure 54: Juvenile raccoon playing with data logger.



Figure 55: Multiple raccoons (n=2) scavenging human 142-13R simultaneously.



Figure 56: Raccoon removing muscle tissue from human 142-13R.



Figure 57: Opossum feeding from scavenging site made by raccoons on human 142-13R.



Figure 58: Raccoon near human 144-13R. Note the scavenging damage to the face and neck.



Figure 59: Raccoon actively scavenging face and neck of human 144-13R.



Figure 60: Opossum feeding from raccoon scavenging site on human 144-13R.



Figure 61: Raccoon returning to human 144-13R to remove muscle tissue from the left arm.

showed more diversity in scavenger type; in addition to the raccoons and opossums, there were also birds and a skunk that were active on the remains (Figures 48 and 51).

Scavenging was anticipated, particularly by raccoons, because of previous observations made at the ARF. However, it was not expected that the raccoons would develop such affinity for some donors in comparison to others. This preferential behavior had a dramatic impact on the segment and total body scores of the human donors, and increased the variation of scores within that species. This complicated the statistical model development, which will be presented in Chapter 8.

Chapter VIII. Statistical and Numerical Results

This chapter details the results of the statistical analyses. A review of data collection as well as raw TBS data are presented in chronological order by trial. Specific data collection dates highlighting differences between species are noted. Hierarchical linear modeling is then used to assess and explain the between species variation, and finally time series models are built and described to determine if the TBS data collected from pigs can accurately predict human patterns.

Trial 1 spring

Scoring

Data collection for Trial 1 Spring began on March 14, 2014, and continued twice daily until 2000 ADH had been reached on April 21, 2014. Photographs and scoring then dropped to once daily until TBS plateaued on May 27, 2014, at which point data collection finished. Figure 62 shows the date and average TBS for the day for all pig and human subjects. Full tables with the individual TBS are presented in appendix A. Dates that are missing indicate days when data could not be collected due to inclement weather issues.

Temperature

Hourly temperature data from the three temperature and humidity data loggers were averaged to calculate a single average daily temperature. Figure 63 shows the temperature trends for the data collection period. As is typical in spring in Tennessee, daily temperatures fluctuated significantly throughout the collection period.

Trial 2 summer

Scoring

Data collection for Trial 2 Summer began on June 14, 2014, and continued twice daily until 2000 ADH had been reached on June 20, 2014. Photographs and scoring then dropped to

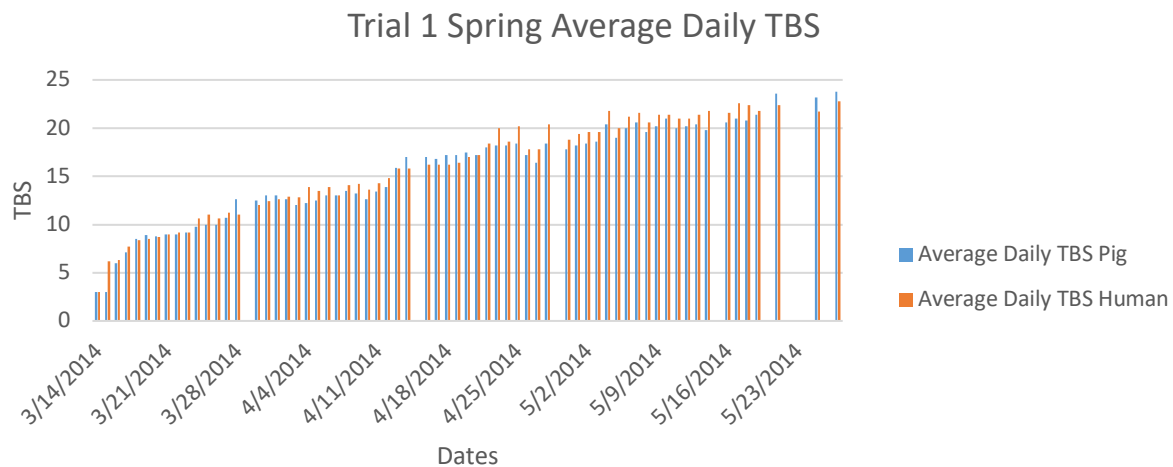


Figure 62: Average Daily TBS for Humans and Pigs in Trial 1 Spring

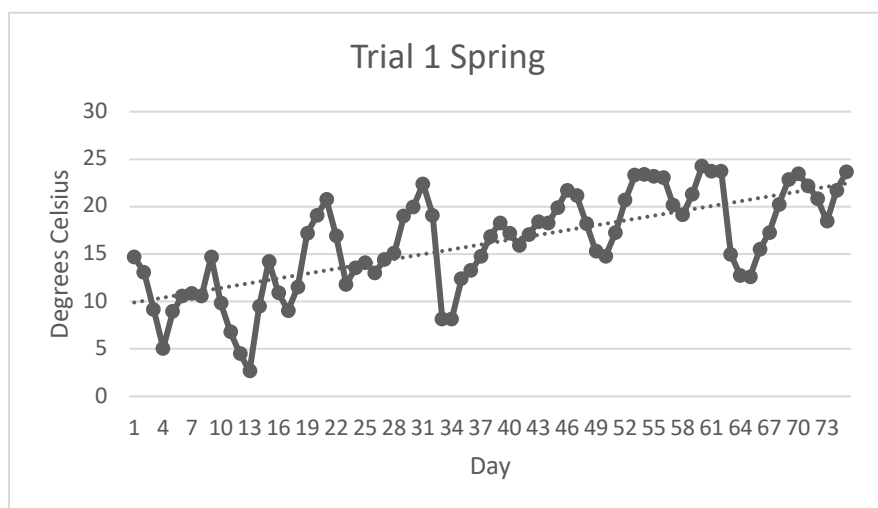


Figure 63: Average daily temperature trends in Trial 1 Spring.

once daily until TBS plateaued on June 30, 2014, at which point data collection finished. Figure 64 shows the date and average TBS for the day for all pig and human subjects during Trial 2 Summer. Full tables with the individual TBS are presented in appendix A.

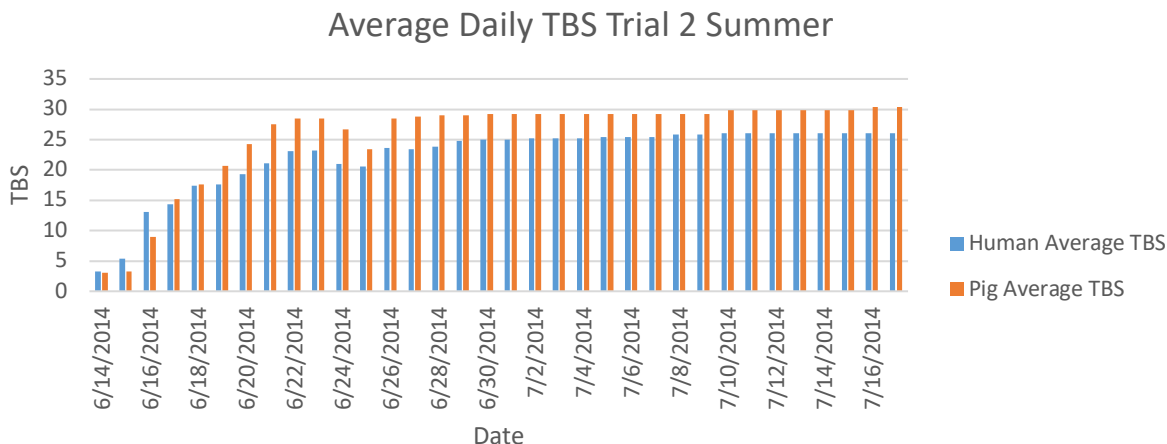


Figure 64: Average human daily TBS and average pig daily TBS.

Temperature

Hourly temperature data from the three temperature and humidity data loggers were averaged to calculate daily temperature. Figure 65 shows the temperature trends for the data collection period. Daily temperatures during the second trial were much more stable than during the first trial and were consistently high.

Trial 3 Winter

Scoring

Data collection for Trial 3 Winter began on December 1, 2014, and continued twice daily until 2000 ADH had been reached on March 22, 2015. Photographs continued until April 14, 2015. Figure 66 shows the date and average TBS for the day for all pigs and human subjects.

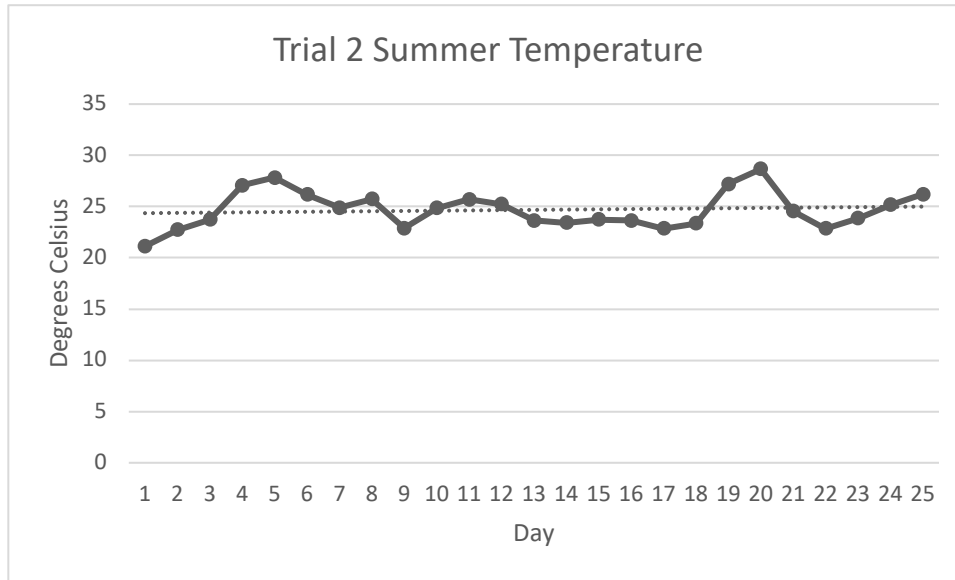


Figure 65: Average daily temperature trends in Trial 2 Summer.

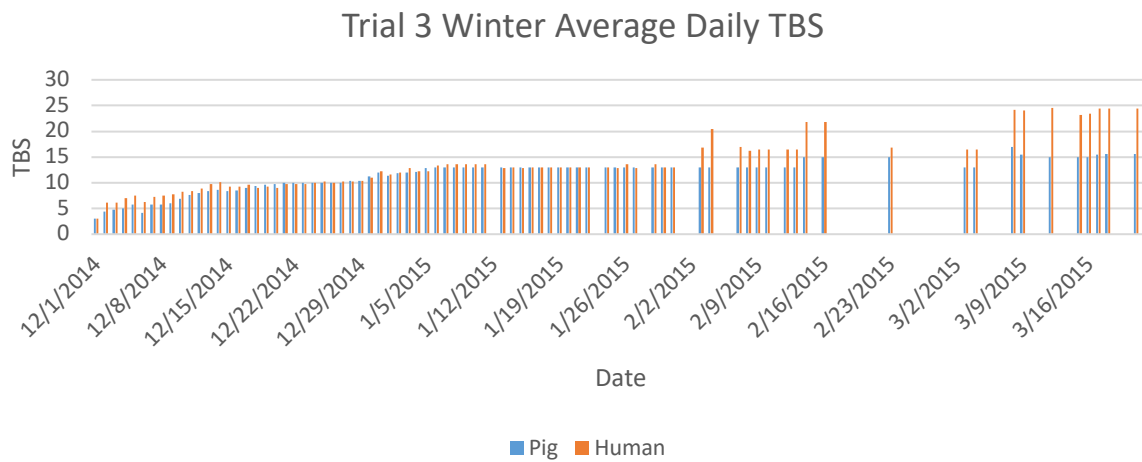


Figure 66: Average human daily TBS and average pig daily TBS.

Full tables with the individual TBS are presented in appendix A.

Temperature

Hourly temperature data from the three temperature and humidity data loggers were averaged to calculate daily temperature. Figure 67 shows the temperature trends for the data collection period. Daily temperatures during the third trial were consistently lower than previous trials. Fluctuations in temperatures were similar to those seen in Trial 1 Spring.

In some observations, the TBS of at least one human and one pig were different enough to produce drastic differences in estimated ADD when calculated using the regression formula of Megyesi and colleagues (2005), such that

$$ADD = 10^{(0.002 \cdot TBS \cdot TBS + 1.81)} \pm 388.16.$$

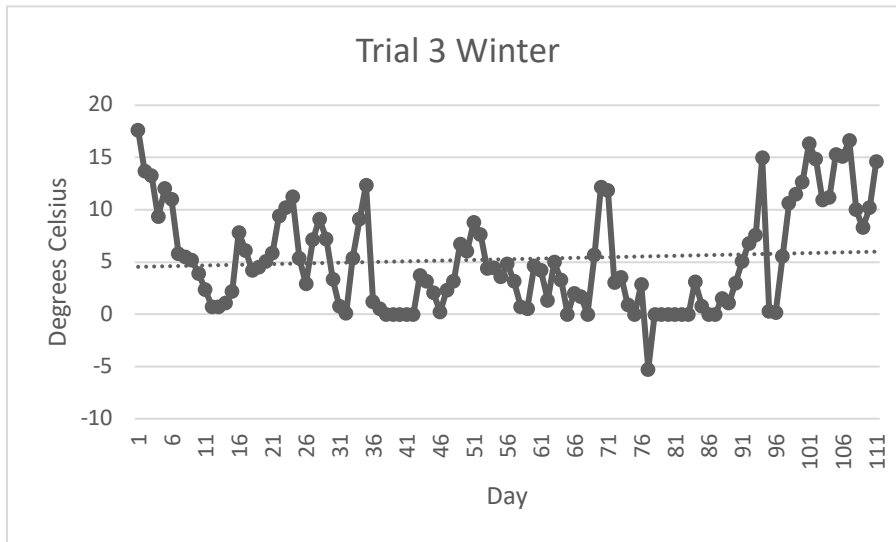


Figure 67: Average daily temperature trends in Trial 3 Winter.

Table 8 shows some selected days from all three trials that most clearly show discrepancies between pig and human subjects. It is important to note that this project does not represent a test of the TBS system, nor of the regression equation from that system used to estimate ADD. The important question here is whether or not data from a pig substitute would

Table 8: Individual TBS examples from all three trials showing the variation between pigs and humans.

Trial	Date	TBS Human	TBS Pig	ADD Human	ADD Pig	PMI Human	PMI Pig
1	15-Mar	8	3	86.69618758	67.29767	7	5
	24-Mar	12	9	125.3141175	93.7562	12	8
	25-Mar	13	10	140.6047524	102.3293	14	8
	9-Apr	16	13	209.8939884	140.6048	19	14
	21-Apr	21	17	492.0395357	244.3431	37	21
	22-Apr	22	17	599.7910763	244.3431	43	21
	27-Apr	23	13	737.9042301	140.6048	51	14
	3-May	22	18	599.7910763	287.0781	43	24
	7-May	19	26	340.4081897	1452.112	27	80
	10-May	19	27	340.4081897	1853.532	27	95
	19-May	20	27	407.3802778	1853.532	31	95
2	15-Jun	8.5	4	90.05337628	69.50243	3	2
	18-Jun	21	13	492.0395357	140.6048	18	5
	19-Jun	25	15	1148.153621	181.9701	45	6
	20-Jun	15	28	181.9700859	2387.811	6	95
	21-Jun	17.5	29	264.5452695	3104.56	10	124
	22-Jun	20.5	31	447.1981518	5395.106	17	215
	23-Jun	20	29	407.3802778	3104.56	16	124
	25-Jun	19	25	340.4081897	1148.154	14	45
	30-Jun	24	30	916.2204901	4073.803	36	163
3	2-Dec	8	3.5	86.69618758	68.31247	7	4
	3-Dec	8	4	86.69618758	69.50243	7	4
	4-Dec	8.5	5	90.05337628	72.4436	8	5
	5-Dec	9	5	93.75620069	72.4436	8	5
	6-Dec	8	3	86.69618758	67.29767	7	4
	7-Dec	8	5	86.69618758	72.4436	7	5
	8-Dec	8	4	86.69618758	69.50243	7	7
	9-Dec	9	4	93.75620069	69.50243	8	7
	10-Dec	9	6	93.75620069	76.2079	8	6
	3-Feb	27	13	1853.531623	140.6048	308	20
	4-Feb	29	13	3104.559588	140.6048	517	20
	7-Feb	27	13	1853.531623	140.6048	308	20
	13-Feb	27	13	1853.531623	140.6048	308	20
	14-Feb	28	13	2387.811283	140.6048	397	20
	16-Feb	28	13	2387.811283	140.6048	397	20
	8-Mar	29	15	3104.559588	181.9701	517	26
	22-Mar	28	13	2387.811283	140.6048	397	20

produce the same data as a human model. The above table demonstrates that pigs are frequently different by a substantial margin. For example, during Trial 2 Summer, most of the pigs skeletonized much more quickly than the humans. One pig in particular, by June 20, 2014 had a TBS of 28, while the least decomposed human only had a TBS of 15. These scores correspond to estimated ADDs of 2387 for the pig and 181 for the human. The stark differences in TBS and resulting ADD are a reminder that many variables can impact the decomposition process, and all of those factors plus their interactions need to be considered when assessing if pigs are a direct replacement for humans in decomposition and taphonomic research.

Statistical analyses

Hierarchical linear modeling

Trial 1 spring

Hierarchical linear modeling is useful when data are nested within groups and when repeated measurements are taken. As applied to this project, individuals are grouped into two species and the body segment and total body scores are repeated measures. For all trials, each body segment was modeled independently to assess differences between pigs and humans. Body segment was evaluated as opposed to total body score in order to determine if differences in decomposition patterns were being more heavily influenced by one segment over another. This was of interest as it helped to assess the hypothesis that pigs and humans would differ in their decomposition patterns on the basis of anatomical and physiological variations such as weight distribution. SAS version 9.4 was used to construct all HLMs. Generalized equations for HLM are presented in Chapter 5.

In Trial 1 Spring, significant differences between species were identified for the trunk, but not for the head and neck or limbs. Significance is denoted by the p-value, with alpha set at .05 for 95% confidence and .01 for 99% confidence. Here, any p-value of less than .05 was used

to determine that a variable was an important driver of segment score variation. Table 9 shows the p-values for the fixed and random effects. P-values that met the criteria for significance at the .05 level are highlighted in bold. After the analyses were run, a decision was made to also run a correction factor on the p-values. When multiple effects are tested and multiple p-values are generated, the significance level often needs to be adjusted to achieve the desired confidence level. For the HLMs presented here, Holm's method, also known as stepwise Bonferroni correction, was run. This method has the advantages of being able to detect family level error and reduces the probability of determining a variable is significant when it is not (reduces type I error) (Statistics Solutions, 2017). The Holm-Bonferroni stepwise method is also more powerful than the traditional Bonferroni correction, which is why it was selected for use here.

For all trials, the fixed effects analyzed included species, time, and temperature. Fixed effects means that the variables were anticipated to change in the same way across both species. As an example, the time or temperature would change at the same rate for both species. Scavenging was modeled as a random effect, so equal change across species was not assumed. For each segment, time and temperature had significant effects on the values of the segment scores. The estimate column (column 1) of the table shows the log odds (a measure of likelihood) that the specified variable will impact the segment score. For example, Time has an estimate of 0.5632, the highest of the effects tested. This indicates a greater probability that Time will impact the segment score. In the context of decomposition, this is to be expected. Decomposition is a time directed process, and the scores should be changing as time progresses. Numerator degrees of freedom (D.F. in column three) and denominator degrees of freedom (den D.F. in column four) are also presented in Table 9. Degrees of freedom refer to how many ways a solution may vary without violating the constraints of the test. Column five of Table 9 presents

Table 9: p-values for fixed effects from the Hierarchical Linear Modeling of Trial 1 Spring.

Tests of Effects-Trial 1 Spring Head and Neck						
Effect	Estimate	D.F.	Den D.F.	F Value	P-values	Holm's
Species	0.2600	1	78	1.37	0.2459	0.4916
Time	0.5632	1	9	118.07	<.001	0.0004
Scavenging	-0.02868	1	1	0.03	0.8912	0.8634
Temperature	0.1195	1	9	11.36	0.0083	0.0249
Tests of Effects-Trial 1 Spring Trunk						
Effect	Estimate	D.F.	Den D.F.	F Value	p-values	Holm's
Species	-0.3762	1	78	5.85	0.0179	0.0342
Time	0.4271	1	9	144.18	<.001	0.0004
Scavenging	0.2811	1	1	9.02	0.2047	0.0108
Temperature	0.0589	1	9	8.51	0.0171	0.0342
Tests of Effects-Trial 1 Spring Limbs						
Effect	Estimate	D.F.	Den D.F.	F Value	p-values	Holm's
Species	0.5259	1	78	2.80	0.0984	0.1284
Time	0.2741	1	9	40.65	<.001	0.0004
Scavenging	0.2336	1	1	3.29	0.03206	0.1284
Temperature	0.07377	1	9	8.54	0.0170	0.0516

the F value, which is a measurement of the fit of the model. If the p-value is greater than the specified F value for that row, then a model with the intercept only (and without the variable being tested) would be a better fit to the data. In the analyses discussed here, the goal was to determine if specific factors were driving variation in observed decomposition as measured by segment score. The goal was not to build the best model. Therefore, nonsignificant variables are still reported and are discussed in Chapter 9.

Table 10 shows the estimated least square mean for each body segment. This estimate indicates how the two species differed. Head and neck estimates are almost identical for the two species. In the trunk, humans are estimated to be less decomposed than the pigs, while for the limbs the humans are estimated to have a higher score, which indicates greater decomposition.

Table 10: Estimates from the Hierarchical linear modeling for Body Segments in Trial 1 Spring subjects.

Species	Head and Neck Estimate	Trunk Estimate	Limb Estimate
Human	6.6845	4.7823	5.0566
Pig	6.4245	5.1585	4.5307

Trial 2 Summer

In Trial 2 Summer, there were no significant differences between the species for any of the segments. Only time was consistently significant across segments. Scavenging was a significant driver of variation in the trunk. Unlike Trial 1 Spring, temperature was not significant for any of the body segments. Table 11 shows the log odds (estimates), degrees of freedom and p-values for the fixed effects. Table 12 shows the least squares means estimates for each segment. Humans were estimated to have lower scores than pigs for all body segments.

Table 11: p-values for Hierarchical Linear Modeling for Trial 2 Summer.

Tests of Effects-Trial 2 Summer Head and Neck						
Effect	Estimate	D.F.	Den D.F.	F Value	p-values	Holm's
Species	-1.6091	1	15	9.99	0.0065	0.0153
Time	1.0944	1	9	29.59	0.0004	0.0016
Scavenging	-0.9791	1	4	5.79	0.0739	0.0530
Temperature	-0.8660	1	9	0.94	0.3586	0.3586
Tests of Effects-Trial 2 Summer Trunk						
Effect	Estimate	D.F.	Den D.F.	F Value	p-values	Holm's
Species	-0.1295	1	15	0.04	0.8354	1.0000
Time	1.2096	1	9	42.61	0.0001	0.0004
Scavenging	-0.9925	1	4	7.86	0.0486	0.0339
Temperature	-0.5218	1	9	0.48	0.5071	1.0000
Tests of Effects-Trial 2 Summer Limbs						
Effect	Estimate	D.F.	Den D.F.	F Value	p-values	Holm's
	-0.3655	1	15	1.05	0.3214	0.6344
Time	0.8431	1	9	35.85	0.0002	0.0008
Scavenging	-0.3825	1	4	1.71	0.2610	0.6078
Temperature	-0.5173	1	9	0.68	0.4304	0.6344

Table 12: Estimates determined from the Hierarchical Linear Modeling for Trial 2 Summer.

Species	Head and Neck Estimate	Trunk Estimate	Limb Estimate
Human	8.5289	7.4980	6.3270
Pig	10.1380	7.6275	6.6925

Trial 3 Winter

In Trial 3 Winter significant differences were found in between species for the trunk and limbs. Time was significant across all segments. Scavenging was a significant driver of variation in the trunk, and temperature was significant for the limbs. Humans were estimated to have

lower decomposition scores than pigs for all body segments. Table 13 shows the log odds for the effects having an impact on the segment score, as well as the degrees of freedom and the p-values to indicate significance. Table 14 shows the estimated segment scores for each area.

Humans are consistently estimated to have lower scores than the pigs.

Table 13: p-values for fixed effects from Hierarchical Linear Modeling of Trial 3 Winter.

Tests of Effects-Trial 3 Winter Head and Neck						
Effect	Estimate	Number of D.F.	Dependent D.F.	F Value	p-values	Holm's
Species	-0.1816	1	129	0.19	0.6655	0.6655
Time	0.3609	1	9	66.23	<0.0001	0.0004
Scavenging	-0.06396	1	129	2.08	0.1520	0.4560
Temperature	-0.02508	1	9	1.15	0.3110	0.6220
Tests of Effects-Trial 3 Winter Trunk						
Effect	Estimate	Number of D.F.	Dependent D.F.	F Value	p-values	Holm's
Species	-0.6871	1	129	6.73	0.0106	0.0212
Time	0.2440	1	9	38.88	0.0002	0.0008
Scavenging	-0.09387	1	129	8.70	0.0038	0.0114
Temperature	-0.00608	1	9	0.06	0.8115	0.8115
Tests of Effects-Trial 3 Winter Limbs						
Effect		Number of D.F.	Dependent D.F.	F Value	p-values	Holm's
Species	-0.5148	1	129	6.57	0.0115	0.0345
Time	0.2546	1	9	64.56	<0.0001	0.0004
Scavenging	-0.03548	1	129	2.19	0.1417	0.1417
Temperature	-0.05776	1	9	8.97	0.0151	0.0345

Table 14: Estimates of segment scores for Trial 3 Winter.

Species	Head and Neck Estimate	Trunk Estimate	Limb Estimate
Human	5.3044	3.9286	3.7474
Pig	5.4860	4.6157	4.2622

Time series- dynamic linear regression

SAS version 9.4 was used to develop predictive models for the pig data and the human data from each trial. Daily TBS data was used along with daily average temperature, presence or absence of insect activity and average estimated minimum number of scavenging events. Multiple models were tried, but only the best fit models are presented here. Models were developed on a holdout sample, which means that a subsection of the collected data was not used

to build the model. In Trials 1 and 3, the last seven days were left out of the training sample (the data used to build the model) and in Trial 2 Summer, the last five days were withheld. Fewer days were withheld in Trial 2 Summer due to fewer days of data being collected and still needing a robust sample to use for model development. The benefit to this method is that the forecasted values predicted by the models can then be compared to the actual data in the holdout sample. Percent difference, square error, and mean average percent error (MAPE) quantify the difference between the predicted or forecasted values and the actual values. These error statistics give a stronger indicator of model performance than examination of model fit statistics alone.

For Trial 1 Spring, the best fit model for the pig data had an autoregressive term of 1 and a moving average term of 3, or ARIMA (1, 0,3)(0,0,0)₇. An autoregressive term is used when the explanatory variables are time lagged values of the forecast variable (in this research, previous TBS helps to predict future TBS) and a moving average term smooths the past history data to remove random variation and help center the model on true sources of variation (Makridakis et al., 1998). An autocorrelation check for white noise also demonstrated that the series is highly autocorrelated, or dependent upon past values. This is not surprising as decomposition is a progressive process, and temperatures in the spring in Tennessee tend to gradually warm, leading to a slowly but consistently increasing TBS. White noise refers to the amount of variation explained in the series purely by randomness. If the series had been found to have no significant autocorrelation, then the series would be deemed entirely random (or entirely white noise) and there would be no need to fit a model. The autocorrelation (ACF) and partial autocorrelation (PACF) plots presented in Figures 68 and 69 help confirm that the model benefits from both an autoregressive (AR) and a moving average (MA) term. Examining the ACF plot shows a large spike in the first three columns, suggesting an MA term of 3. The overall pattern decreases

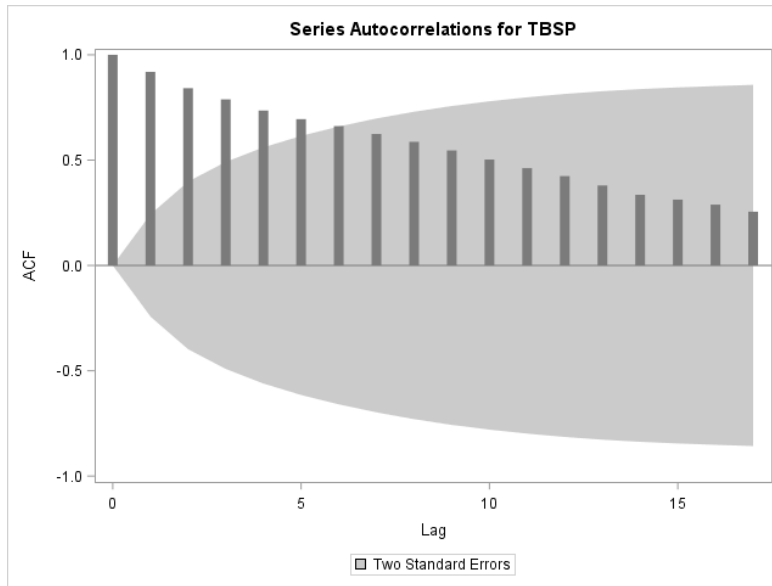


Figure 68: ACF plot for pig model, Trial 1 Spring showing lags where a Moving Average term is needed. Note how the series decreases quickly, showing a strong autocorrelation relationship.

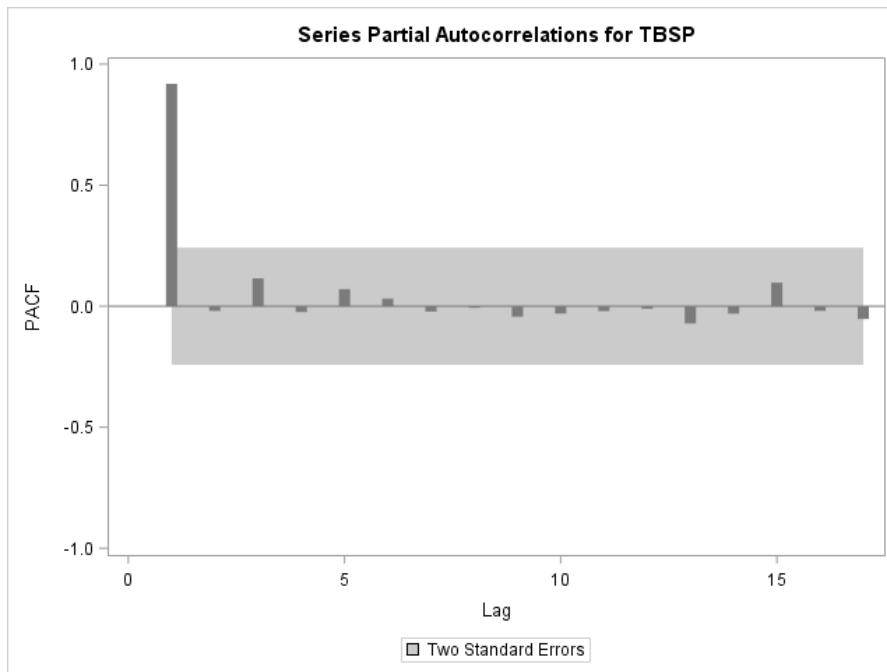


Figure 69: PACF plot for pig model, Trial 1 Spring showing the Autocorrelation term needed. Note how there is a strong spike at the first column, and then the columns cluster close to 0.

quickly, which indicates that the series is stationary, or not needing to be transformed in order to be modeled well. The PACF plot shows a large spike at column 1, which indicates that an AR term of 1 may be sufficient to explain the variation.

In addition to the AR and MA terms in the model, several other variables were also included as dynamic regressors. A dynamic regressor can be defined as an explanatory variable that effects a forecast variable over several time periods (Makridakis et al., 1998). In the decomposition system considered here, temperature, scavenging, insect activity and trend (time) were all included as dynamic model parameters. A dynamic regression model allows for current and past values of explanatory variables to influence forecast variables. It is not surprising that temperature, for example, has a dynamic relationship with TBS. It is also important to note that forecast variables cannot influence explanatory variables. As TBS does not have any influence on the factors included as dynamic regressors, this relationship criterion is satisfied. Seasonality in the series was expected and modeled in two components. A weekly and daily seasonal aspect were included to capture variation on a broad and fine scale, respectively by accounting for the variation within a month and within a week. After building the model, a chi-square test was used to assess autocorrelations in the residuals. The null hypothesis that no autocorrelation exists was supported for Trial 1 Spring, meaning that the pattern in the residuals is white noise, and the model terms are sufficient. A more complicated model is therefore not necessary. Table 15 shows the results of the autocorrelation tests.

The lags represent how many previous data points were assessed for autocorrelation. The p-value indicates whether or not the hypothesis could be rejected with statistical significance (alpha was set at .05). Chi-square values and degrees of freedom for the test are also presented.

Table 15: Autocorrelation check of residuals for pig model in Trial 1 Spring.

Autocorrelation Check of Residuals			
To Lag	Chi-Square	Degrees of Freedom	P-value
6	2.30	4	0.6811
12	7.75	10	0.6536
18	13.17	16	0.6601
24	14.91	22	0.8662

As the model had been found to be sufficient in terms of its parameters, it was then assessed for goodness of fit to the data. This was done by examining the predicted (or forecasted) values calculated by the models compared to the actual values from the holdout sample. The actual mean value from the holdout was calculated and the percent error, square error (actual minus predicted values, squared), sum of square error and mean average percent error (MAPE) were computed. Table 16 shows the goodness of fit assessment for the pig model from Trial 1 Spring. It also includes a measure of variation in the actual values in the column marked “SS”. This calculation is the absolute value of the actual minus the average, squared. Note that SS assesses how well the model based on pig data was able to predict pig values. It does not evaluate if the pig model was successful in predicting human patterns. Evaluating the model on this basis is important because if decomposition research was being conducted with pig substitutes only, then the models would be developed strictly with pig data and would be evaluated based on the model’s fit to the pig values. Therefore, it was important to first create the best possible model for the pig data to simulate research done using an animal proxy only. The fit of the model data to the actual data can also be represented graphically. Figure 70 shows the actual values for pig TBS from Trial 1 Spring in the circles, with the predicted values overlaid as

Table 16: Goodness of fit model assessment from pig model for Trial 1 Spring.

Trial	Species	Actual (Holdout)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
1	Pig	22.4	20.8	22.91	0.071429	2.56	0.26449	19.06	3.028571	5.02%
		22.4	20.9		0.066964	2.25	0.26449			
		22.4	21.6		0.035714	0.64	0.26449			
		22.4	21.8		0.026786	0.36	0.26449			
		24.2	21.2		0.123967	9	1.653061			
		23.2	21.6		0.068966	2.56	0.081633			
		23.4	22.1		0.055556	1.69	0.235918			

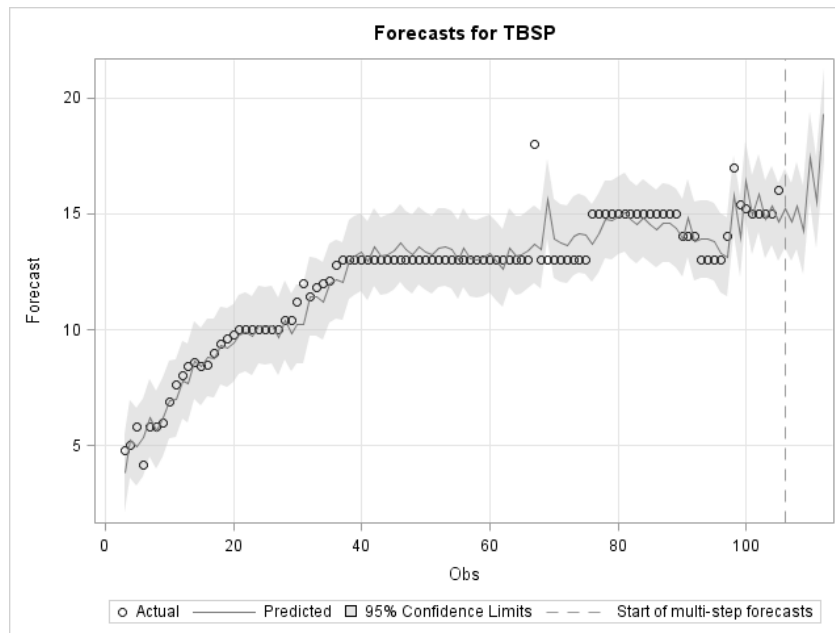


Figure 70: Predicted versus actual TBS values for pig data in Trial 1 Spring, with 95% C.I. values represented by the solid line. A 95% confidence interval for the predicted data is depicted in the shaded area. The dashed line towards the right of the graph indicates where the actual values ended and the predicted values began.

a line.

Examining the graph above shows that the model did track the overall pattern in the pig data, but missed a few aspects, such as a plateau that occurred in the TBS as well as a couple of outliers towards the end of the data collection period. Overall, though, this model tracked the actual data well and would be considered successful.

The primary question of interest for these models is whether or not a model developed solely from pig data would be able to track and predict human patterns well. In order to assess this, the predicted values derived from the pig model in Trial 1 Spring were compared to the actual TBS values from the averaged human data. A Spearman's correlation coefficient was used to determine the strength of the relationship between the human and pig data and the statistical significance of the relationship. For Trial 1 Spring, the pig data was found to be 0.97 and was statistically significant with a p-value less than .001. This suggests that the pig model did a very good job predicting human patterns. Figure 71 shows the plotted human data, represented by the circles, compared to the line of predicted values based on the pig data. It is important to note that the Spearman's correlation coefficient relies on a linear relationship existing between the two data sets. For this reason, the human TBS were plotted against the forecasted pig TBS (depicted in Figure 72). There does appear to be a linear relationship for Trial 1 Spring, so the high correlation is valid.

Models were developed for the human data for Trial 1 Spring in the same manner as was done for the pig data. A different model was found to be the best fit for the human data, in an ARIMA (1,0,0)(0,0,7)₇. In this model, a seasonal moving average was needed to adequately capture the variation. That is expressed in the previous notation by the seven in the second set of parentheses. Non-seasonal parameters appear in the first set of parentheses, and seasonal

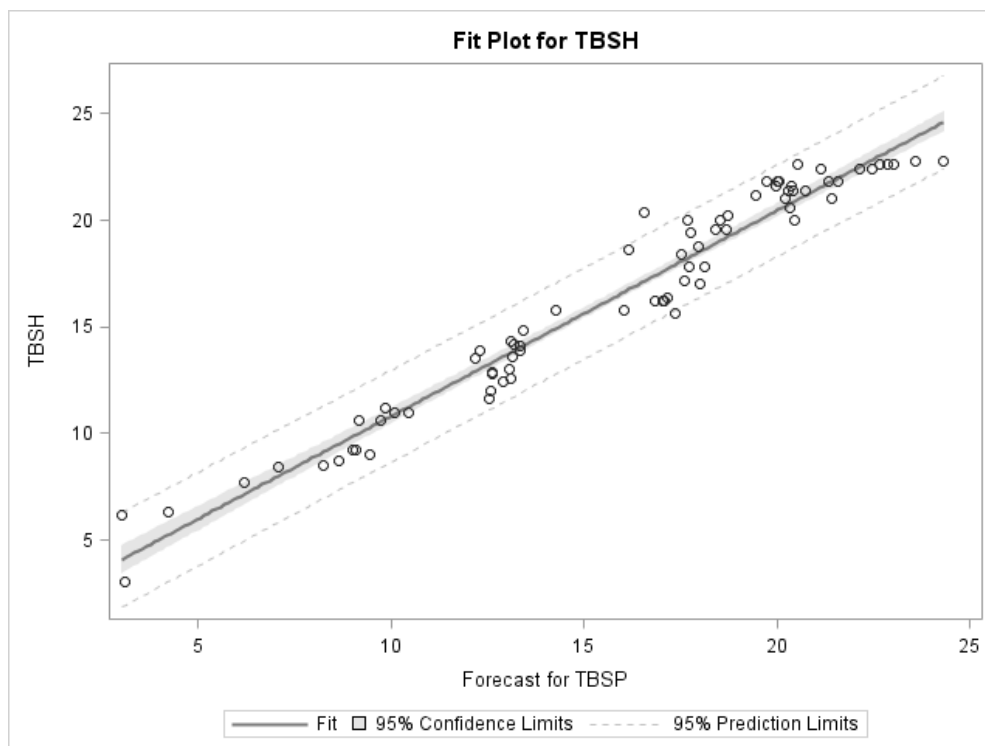


Figure 71: Actual human TBS values from Trial 1 Spring compared to the forecasted fit line developed from the pig model.

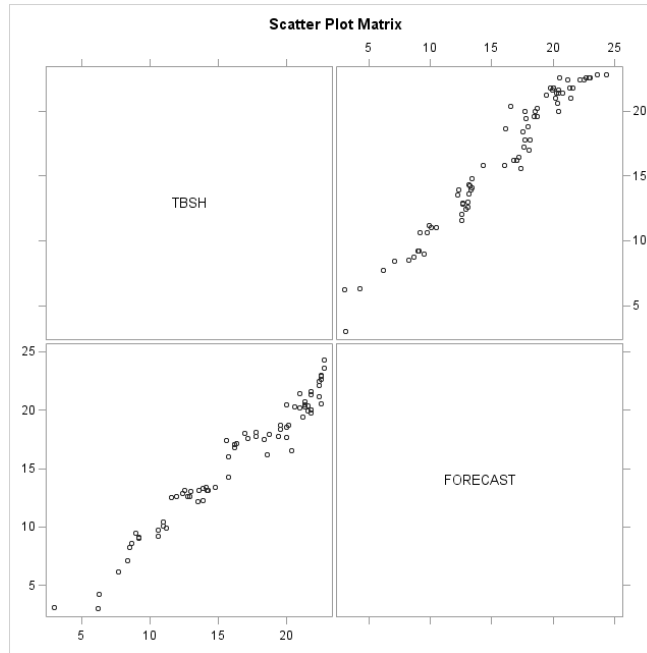


Figure 72: Actual human TBS values plotted against forecasted pig TBS to check for a linear relationship for Trial 1 Spring.

parameters in the second. This model was a better fit for the actual human TBS values, with a mean average percent error of only 2.34%. This reflects that even though the pig model was able to reflect the human data well, a model developed on human data is still superior in predicting human patterns. Figure 73 shows the predicted human values compared to the actual human TBS values. Table 17 presents the full complement of all six models that were developed for the pigs and humans for each trial. ACF and PACF plots for the models as well as autocorrelation checks for the residuals and white noise assessments are available in the appendix. Goodness of fit statistics were computed for each model following the same procedures as described above. Table 18 presents the model assessments for all models.

Spearman's correlation coefficients were calculated for the predicted pig values compared to the actual human TBS for Trials 2 and 3 just as in Trial 1 Spring. For Trial 2 Summer, the correlation was 0.95158, with a p-value less than 0.0001, suggesting a very strong

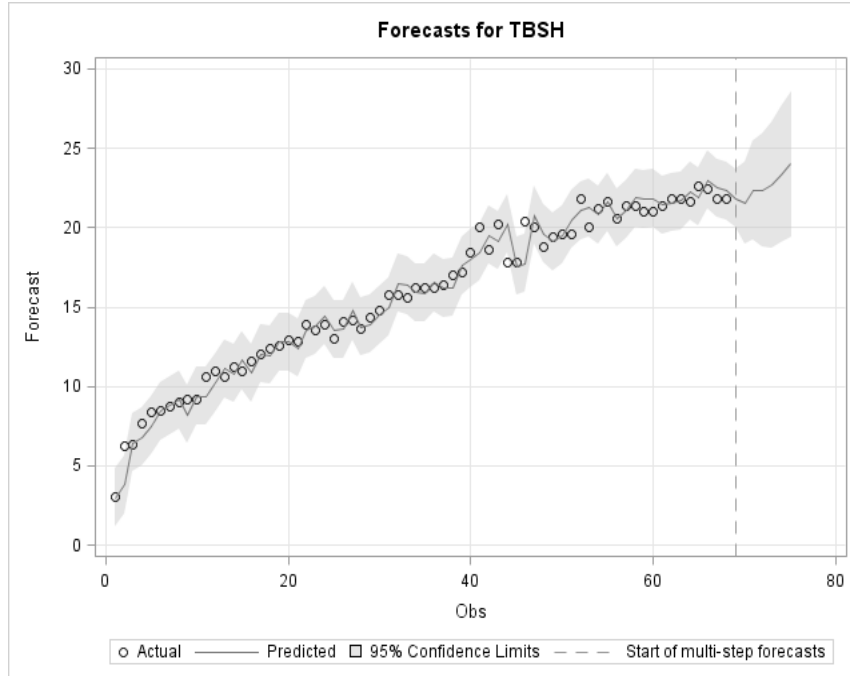


Figure 73: Actual human TBS values in circles compared to predicted TBS values in the line. 95% confidence interval for predictions in gray. Note the difference in pattern of the human values as compared to the pig values from Figure 70.

Table 17: Models for pigs and humans for each trial.

Trial	Species	Model
1	Pig	$(1,0,3)(0,0,0)_7$
1	Human	$(1,0,0)(0,0,7)_7$
2	Pig	$(1,0,3)(0,0,0)_7$
2	Human	$(1,0,3)(0,0,0)_7$
3	Pig	$(2,2,2)(0,0,0)_7$
3	Human	$(0,1,4)(0,0,0)_7$

Table 18: Model fit statistics for all models for all three Trials.

Trial	Species	Actual (Hold out)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
1	Pig	22.4	20.8	22.91	0.071429	2.56	0.26449	19.06	3.028571	5.02%
		22.4	20.9		0.066964	2.25	0.26449			
		22.4	21.6		0.035714	0.64	0.26449			
		22.4	21.8		0.026786	0.36	0.26449			
		24.2	21.2		0.123967	9	1.653061			
		23.2	21.6		0.068966	2.56	0.081633			
		23.4	22.1		0.055556	1.69	0.235918			
Trial	Species	Actual (Hold out)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
1	Human	22.4	21.8	22.6	0.026786	0.36	0.04	3.05	0.16	2.34%
		22.4	21.5		0.040179	0.81	0.04			
		22.6	22.3		0.013274	0.09	0			
		22.6	22.3		0.013274	0.09	0			
		22.6	22.7		0.004425	0.01	0			
		22.8	23.3		0.02193	0.25	0.04			
		22.8	24		0.052632	1.44	0.04			

Table 18: (Continued)

Trial	Species	Actual (Holdout)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
2	Pig	29.8	31.1	30.1	0.0436 24161	1.69	0.09	39.2 5	0.36	9.54%
		29.8	33.2		0.1140 9396	11.56	0.09			
		30.4	32.6		0.0723 68421	4.84	0.09			
		30.4	35		0.1513 15789	21.16	0.09			
Trial	Species	Actual (Holdout)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
2	Human	26	25.5	26	0.0192 31	0.25	0.00	18.4 6	0	6.35%
		26	25		0.0384 62	1	0			
		26	27.1		0.0423 08	1.21	0			
		26	30		0.1538 46	16	0			
Trial	Species	Actual (Holdout)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
3	Pig	15	15.2	15.485 71	0.0133 33	0.04	0.235918	19.4	0.308571	4.20%
		15.4	14.6		0.0519 48	0.64	0.007347			
		15.6	15.3		0.0192 31	0.09	0.013061			
		15.6	14.3		0.0833 33	1.69	0.013061			
		15.6	17.4		0.1153 85	3.24	0.013061			
		15.6	15.5		0.0064 1	0.01	0.013061			
		15.6	19.3		0.2371 79	13.69	0.013061			
Trial	Species	Actual (Holdout)	Predicted	mean(act)	% diff	Square Error	SS	SSE	SST	Holdout MAPE
	Human	23.4	22.2	24.257 14286	0.0512 82	1.44	0.734694	9.47	0.857143	4.77%
		24.4	23.1		0.0532 79	1.69	0.020408			
		24.4	23.2		0.0491 8	1.44	0.020408			
		24.4	23.2		0.0491 8	1.44	0.020408			
		24.4	23.3		0.0450 82	1.21	0.020408			
		24.4	23.2		0.0491 8	1.44	0.020408			

relationship. For Trial 3 Winter, the correlation was 0.92875, and again was statistically significant with a p-value less than 0.0001. However, for both of these trials, when the predicted pig values were plotted against the human TBS values it was demonstrated that a linear relationship did not exist (shown in Figures 73 and 74). Instead, for Trial 2 Summer, the two data sets had a quadratic relationship, and for Trial 3 Winter, a cubic relationship. This indicates that the strong correlation identified by the Spearman's coefficient is not accurate and does not give a true indication of the ability of a pig model to predict human patterns. The human models are much more successful in predicting human values. All of the statistical results as well as the insect activity pattern and scavenging activity will be discussed and interpreted in detail in the next chapter. Figure 74 shows the predicted human values as compared to the actual values and the confidence interval for Trial 2 Summer. Figure 75 depicts the predicted and actual pig values for Trial 2 Summer. Note the similarity in series between both species. This was the only trial for which the same model worked for both sets of data. Figures 76 and 77 show the predicted compared to the actual values for the human and pig data sets for Trial 3 Winter, respectively.

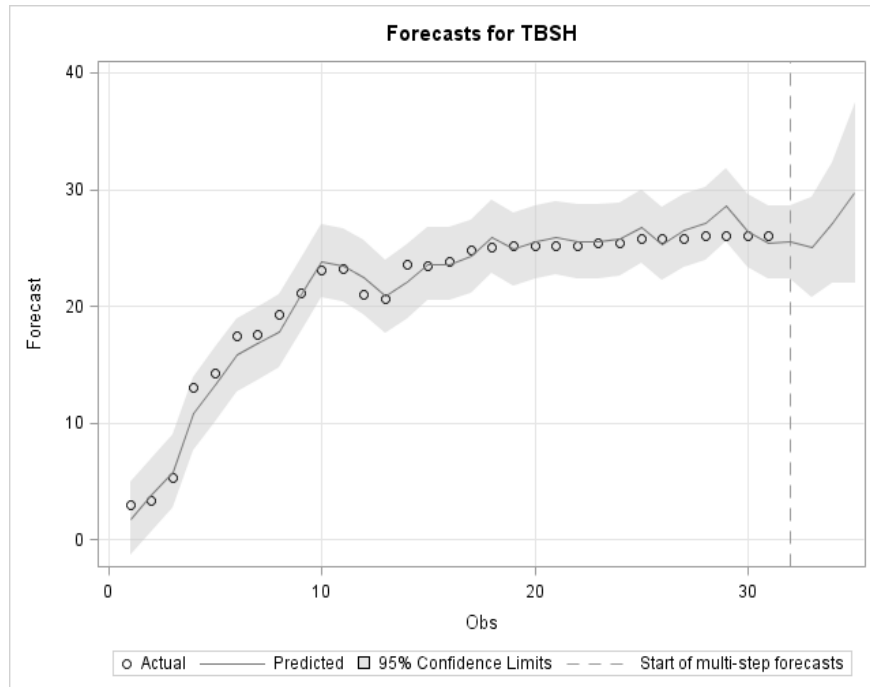


Figure 74: Actual human TBS values in circles compared to the forecasted fit line for Trial 2 Summer. Confidence interval is in gray.

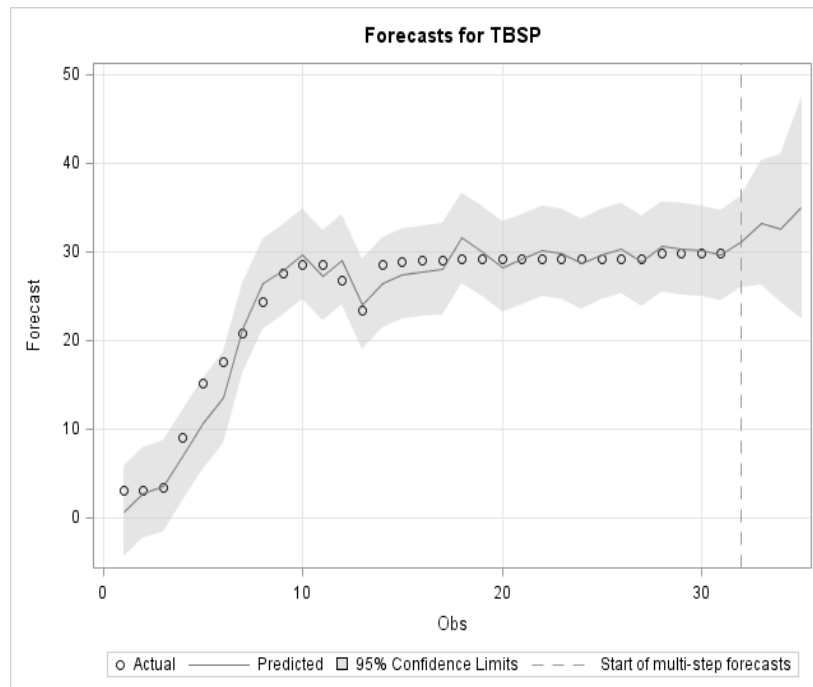


Figure 75: Actual pig values in circles compared to the forecasted fit line. The 95% C.I. is in gray. Data is for Trial 2 Summer.

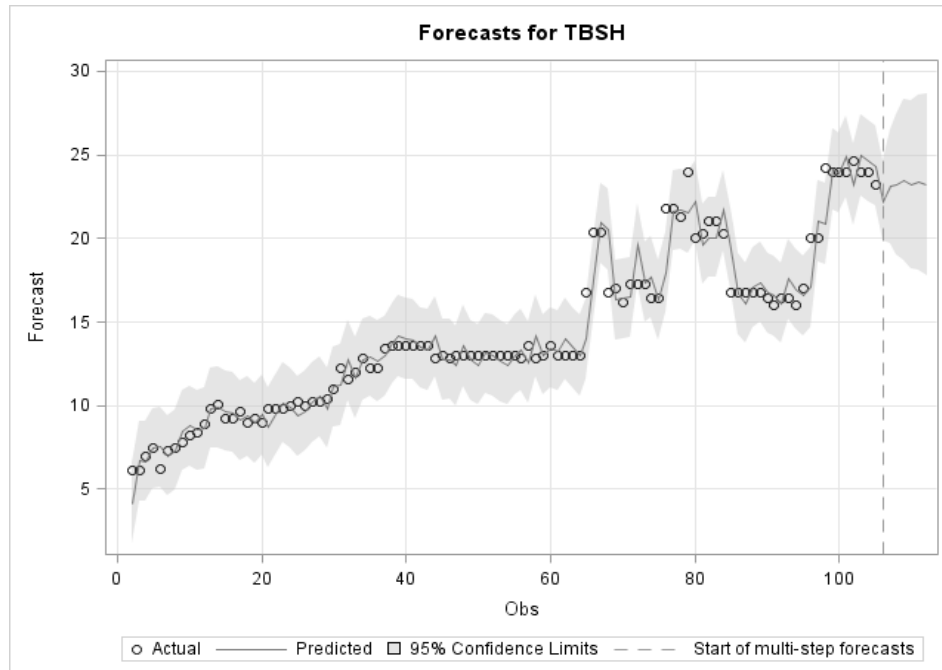


Figure 76: Actual human values in circles compared to the forecasted fit line. The 95% C.I. is in gray. Data is for Trial 3 Winter.

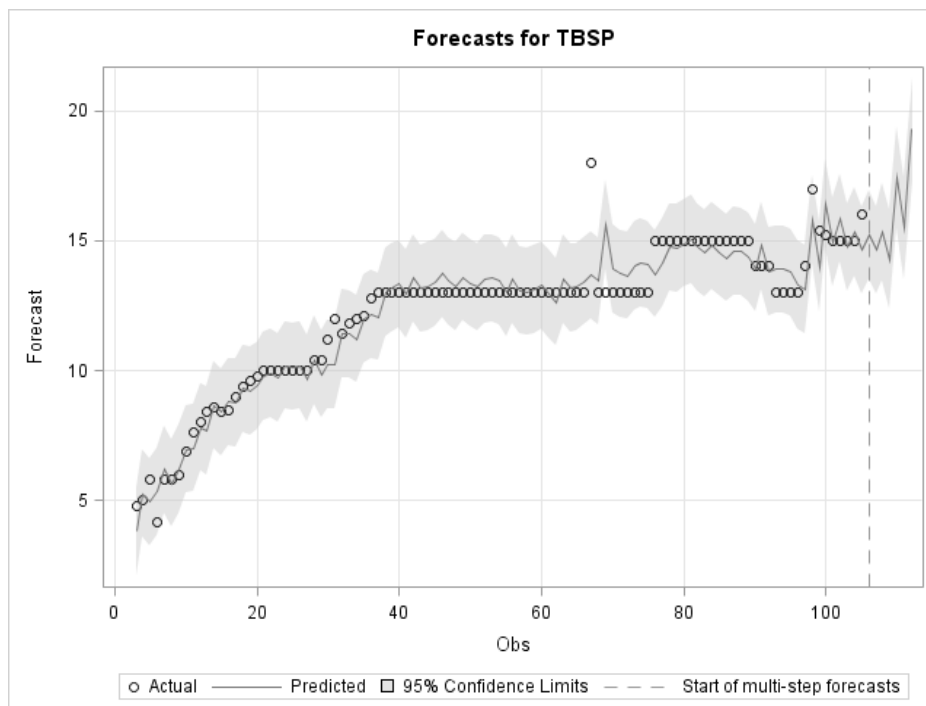


Figure 77: Actual pig values in circles compared to the forecasted fit line. The 95% C.I. is in gray. Data is for Trial 3 Winter.

Chapter IX. Discussion

The purpose of this project is to assess if there are significant differences in the decomposition progression of pigs compared to humans in order to determine if pigs can be used as a substitute for humans in taphonomic research. Previous studies have sought to compare pigs to humans in terms of aspects of decomposition (Notter et al., 2009, Wang et al., 2017). These studies have looked at the types of insects attracted to various carrion types (Schoenly et al., 2007), and other studies have examined the differences and similarities in microbiological activity (Parkinson, 2009, Metcalf et al., 2016). The problem is that these previous studies have not examined decomposition along multiple axes as to determine if domestic pigs can directly substitute for human remains in all types of decomposition research. Decomposition is a complicated process that is impacted by multiple variables all affecting each other and producing a variety of patterns. Assessing if domestic pigs and humans are similar in overall patterns of decomposition such that the species are interchangeable requires a theoretical shift in the approach to experimental taphonomic studies and requires large scale direct comparisons of the two species across multiple variables of interest.

TBS results

Looking at the individual TBS and segment scores for the humans in each trial clearly shows that humans are much more variable than the pigs. The variability alone is not the only potential problem. Frequently the estimated ADD (and thus the resulting estimated PMI) were considerably different between individual human and pig specimens. This is in part due to the formula for estimating ADD from TBS. The formula relies on a log transformation of the TBS, so even small variations in TBS can result in large differences in estimated ADD and PMI. Without having some sort of reliable correction factor, using pigs in decomposition and taphonomic research could result in estimation methods with very high errors.

Insect results

Results of this study show that the pattern of insect activity can differ dramatically between two species, largely because of the anatomical differences between the two species that lead to different locations of insect larval masses. One very simple difference is that while the human subjects could easily be placed on their backs on the ground, it was not possible to place the pigs flat on their backs without constructing some sort of barricade. Instead, the pigs were placed on their sides. While this does not seem like it would cause deviations of the decomposition pattern, it did mean that the flies had much easier access to the rectal area of the pigs as compared to the humans. Larval masses were also clearly visible under the tails of the pigs, while any larvae that were in a comparable area on the human subjects were largely unable to be seen and counted during data collection. The variation in positioning also meant that bone exposure for the pigs started at the head and at the rump, while in the humans, first bone exposure was seen at head and at groin. Again, that may seem parallel, but it is crucial to keep in mind that head to rump encompasses the entire body of the pig, while head to groin does not cover the entirety of the human body. Larval activity covering the snout to rump of the pigs impacted the segment scores for every segment of the pigs. The smaller insect coverage on the humans meant that the higher scores corresponding to bone exposure were only seen in the head and neck and trunk, and not the limbs. A discrepancy in insect activity and corresponding TBS supports previous research that indicates that body size can impact decomposition progression (Stuart, 2003). The results presented here also suggest that body positioning is a critical factor that should be considered along with body size.

Scavenging results

The results of the scavenging analysis highlight another critical aspect of human variation in decomposition. In Trial 1 Spring, only two humans were scavenged, and only one human was

scavenged multiple times on multiple sites. There was no clear explanation for why that human was preferentially scavenged. That particular individual that was scavenged repeatedly was no more accessible than any of the other subjects, nor was the time of death different enough to clearly make that individual more attractive to scavengers. Yet the raccoons, and following them, the opossums, very clearly returned to scavenge the one individual preferentially. The same pattern was repeated in the summer, when again only two human individuals and none of the pigs were scavenged. As in Trial 1 Spring, there was nothing about the positioning or outwardly observable variables of the scavenged humans that would neatly explain why they were preferred so strictly. Even in Trial 3 Winter, when all of the humans and eventually all of the pigs were scavenged, there were still noticeable patterns in which certain humans were preferred to others. Raccoon scavenging is a well-documented phenomenon at the ARF; multiple studies have shown that raccoons will heavily scavenge freshly decomposing remains and will continue to scavenge through active decomposition (Synstelién, 2015, Smith, 2015). Synstelién (2015) also observed that raccoon scavenging was heaviest during the winter months.

Entomotoxicology studies have documented that insect activity can be delayed or inhibited by toxins found in remains, and by extension pharmaceutical toxins could dissuade mammalian scavengers as well (e.g. Carvalho et al., 2001). Unfortunately, the complete medical history of the donated human remains was not known, and so it was not possible to determine if medication or a medical condition contributed to the scavenger preference. Another potential concern is that the mammalian scavengers could have been deterred from the pig remains as the pigs were euthanized via lethal injection. However, as all of the pigs were eventually scavenged in Trial 3 Winter it is clear that the pentobarbital that was administered to the pigs at least did not prevent scavenging from happening.

Several recent decomposition studies have taken measures to prevent scavenging explicitly because such animal behavior can disrupt “normal” decomposition progression and make inter-subject comparisons more difficult. It may seem then, that the differences in scavenging preference for different types of carrion could then be ignored. However, the final application of these data must be considered. In an actual forensic setting, there would not necessarily be any barriers to any scavenger type, and so understanding the behavior patterns of these animals could be critical to an accurate estimation of PMI. If researchers consistently prevent scavenging or purposely choose a carrion type that is less attractive to scavengers, they eliminate a potentially critical source of variation. Eliminating variation makes results easier to interpret in the short term, but does not give a complete picture of the intricate nature of decomposition.

Including scavenging behavior and its effects on the rate of decomposition are also critical if taphonomic researchers intend to shift the theoretical focus of decomposition studies. Eliminating difficult to predict variables such as scavenging makes sense in a Newtonian designed study, where the goal is to isolate a single variable and attempt to understand that variable’s impact. A more thorough understanding of decomposition as a process requires that the chaotic nature of interacting variables be included in study and analysis. Scavenging is perhaps one of the most complex variables encountered in taphonomic research as it interacts with other variables such as season, insect activity, geographic location, and time of day and eventually can have a profound impact on the overall progression of decomposition as observed in this project during Trial 3 Winter.

Model results

The results of the hierarchical linear modeling show that the segment scores for pigs and humans did differ significantly in two of the three seasons. The fact that they did not differ

during the summer is not surprising, as very high temperatures lead to rapid decomposition, regardless of species. The similarity observed between humans and pigs in the summer trial also sheds light on the results of the 2007 study conducted by Schoenly and colleagues. In that study, few differences were observed between entomological activity on pigs and humans, and the authors concluded that pigs could be substituted for humans in forensic entomology research. Their study was constrained to a single season, summer. It is possible that if their study had been repeated in other seasons, differences in decomposition between the species would have been observed. The differences in spring and winter in segment scores reflects several areas of variability between the two species. Segment scores differed significantly by species in the trunk for Trial 1 Spring. The distribution of body mass is different in the trunk of pigs as compared to humans, and the human trunks were more likely to mummify with little to no bone exposure, while the trunks of the pigs frequently had moist decomposition with bone exposure. Increased bone exposure in the pigs led to a higher estimated segment score for the trunk.

Applying the TBS data to time series models directly addresses the question of whether the data generated from pigs is reflective of human patterns. The short answer here is no. Different model types with different seasonal differencing, autoregressive terms and moving average terms were best fits to the pig data compared to the human data. The Spearman's correlations did appear to be very strong- most were above .95 with p-values of less than 0.0001, which would seem to suggest that even though there were different model types, the pig and human data are still very close. But Spearman's correlations rely on the assumption that there is a linear relationship between the two sets of data. When actually plotted out and regressed, the assumption of linearity was violated for two of the three seasons. Only the spring data were shown to have a linear relationship. The summer data had a quadratic relationship and the winter

data had a cubic relationship. This means that the Spearman's correlations do not reflect an accurate assessment of similarity between the two species. This violation of assumptions also demonstrates why it is so critical to choose appropriate statistical measures for analyzing decomposition data.

The pig models also did not have consistent error types compared to the human models. As opposed to consistently under-estimating or over-estimating the segment scores and TBS, the pig error did not have a clear pattern. This lack of pattern means that constructing a black box type model will likely not sufficiently address the discrepancy between the two species. It is also crucial to keep in mind that the averaged data was used for both species, which should have made it more possible for the two models to perform comparably even with a few distinct “outliers” (heavily scavenged humans). Ultimately, to address the discrepancy between pig and human decomposition, error rates need to be established. The data collected here does not contain enough of a consistent error pattern to determine error rates that would be useful in developing a correction factor. More replicates of this study across all four seasons are needed to determine usable error rates and corrections.

Seasonality was clearly identified as a critical factor in choosing model parameters and in terms of decomposition progression. Spring started with low temperatures and then increased, summer had consistently high temperatures, and winter started warmer, dropped sharply, and then eventually rebounded. The data collection period impacted the models as well. If the ADH cutoff had been placed at an earlier cutoff marker, then the temperature variations in spring and winter would potentially have been missed. In contrast, if the data collection period had been extended for each season, then the temperatures may have reached a stabilizing point.

Time series analyses are not frequently applied to decomposition studies, although they are a particularly well suited statistic to taphonomic research questions. One of the most important components of time series is that progression over time is incorporated into the analysis. Decomposition is a progressive process, and many decomposition studies are interested in understanding the rate and variability of the process over a given period of time, as opposed to just at a single point. Again, if taphonomic researchers look to complexity science as a theoretical model, time series statistics are frequently incorporated to properly assess and understand complicated processes with multiple interacting variables. Especially as the goal of many decomposition studies is to improve the predictive ability of methods for estimating PMI, statistics which directly investigate the predictive power of the data should be included.

Pig versus human

One of the suggested benefits of using pigs in decomposition research is that they are less complicated than humans (Parkinson, 2009). This is logical since in this study and others the pigs all come from the same farm, are approximately the same age, and have been exposed to the same environmental factors and diet for their entire lives. Humans have a much more individual internal microbiome, influenced by their activity levels, diet, medication, health states, and other environmental factors.

Body composition also differs between pigs and humans. While investigating adipocere formation in the two species, Notter and colleagues documented that there are varying amounts of volatile fatty acids (VFAs) in pigs compared to humans (2009). Differences in the amounts of VFAs led to differences in timing and amount of adipocere formation. The authors of the study conclude that researchers should be cautious in applying results from pig models onto human decomposition processes and the results of this study support that assertion. Pig remains and human remains did not demonstrate identical decomposition trajectories, with humans tending to

mummify more quickly and completely. Pig carrion tended to skeletonize more completely. More research specifically examining the influence of body composition would help to further explain pattern differences. For example, it would be beneficial to be able to determine the ratio of body fat to muscle on either humans or pigs and then address any observed decomposition differences.

Sample size

Biological significance versus statistical significance is another issue worth addressing. Several studies have criticized human decomposition research for drawing conclusions based on small sample sizes (Meurs, 2016). This is a valid concern. But the response from researchers other than Meurs to rely on a human proxy to solve the sample size issue simply replaces one problem with another. It is much easier to get a large sample of domestic pigs (or other proxy species) at the same time, which is extremely convenient for research. However, the data gathered from pig studies may not be directly applicable to human contexts without further investigation and correction.

Megyesi system

The TBS system developed by Megyesi and colleagues was designed specifically for humans, and not for other carrion types. Even using recently developed TBS modifications for pigs would introduce a new complication in attempting to compare results from two different standards. The problem with applying the TBS system to pigs is that the researcher is forced to choose from a set of pre-existing categories, and will therefore pick the one that seems “closest” to correct even if it does not entirely match with what is being observed in person or via photographs.

Pigs have a different anatomical structure than humans, but there is no way to effectively capture this with the TBS categories. For example, when the most noticeable discoloration is in

the ears, there is no option that states “discoloration in inner ears only” so the closest choice would be a category that describes some discoloration in the head and neck. While this may at first seem to be a negligible difference, it effectively smooths the data to make the two species appear to be more similar than they really are. This forced similarity is another reason that the close correlations between the predicted pig values and the actual human values should be interpreted with caution.

A modified version of the Megyesi system has been proposed by Keough et al. (2017) for use in studies where pigs are used instead of humans. As this modification was developed using porcine remains, it is likely that it will be much more accurate for describing pig decomposition in research. The problem of comparing humans and pigs directly to each other is not solved by this modification, however. While the pig system is meant to be complementary to the TBS system, it is not identical, and incorporates elements not included in the TBS system such as “insect larvae present” (Keough et al., 2017). While the TBS system of Megyesi and colleagues (2005) incorporates the effect of insect activity in the morphological indicators of decomposition, it does not include any descriptions of insect presence or absence. In order to compare pigs and humans, a researcher would need to either apply the human TBS to both species, the pig TBS to both species or use two separate scoring systems for each species, and then try to compare the scores. Any of these options introduce error.

Theory

The timing of taphonomic studies is sometimes problematic. Most decomposition studies are undertaken in the summer, precisely because decomposition will proceed quickly and this will allow the research to progress in a timely fashion. Forensic cases, in contrast, are not confined solely to summer months, and it is crucial that other seasons be represented in research,

regardless of the onerous nature of attempting to patiently observe slow decomposition in the winter.

While it might seem beneficial for research settings to keep as many variables constant as possible, the eventual application to forensic cases will reintroduce all the complexity that humans bring. Domestic pigs may provide a helpful starting point to investigate whether certain variables will influence decomposition, but then those studies should also be applied to humans to see if the results are the same in both species. This is where it comes back to the difference between Newtonian studies and complexity science-based research. When we are looking at an individual piece of the decomposition puzzle, for example, types of insects that are commonly found in specific regions, pigs could be used. Conversely, when attempting to investigate factors that impact the rate of decomposition in order to better estimate PMI, it would be beneficial to work with human remains.

Hypotheses

The first hypothesis, that human subjects will vary more within species than pig subjects, was supported by the TBS data and the scavenging activity. Individual scores for the humans were less consistent than those of the pigs. Specific humans were also more likely to be scavenged compared to other humans, while no such preference appeared to exist for the pigs. This discrepancy between species was highlighted in the statistical analyses, both in the hierarchical linear modeling and in the dynamic regression models. In the hierarchical linear modeling, significant differences were identified between species for Trials 1 and 3, with only Trial 2 Summer not showing significant differences according to species. The lack of distinction between species in Trial 2 Summer is most likely the result of rapid decomposition that progressed too quickly for interspecies differences to be detected.

Dynamic linear regression identified distinctions in decomposition progression between pigs and humans. The models constructed to best represent the decomposition sequence were not identical between the species, and the predicted values produced by the models constructed with pig data did not accurately reflect the actual values from the human data.

The second hypothesis was partially supported. Estimation of PMI from the TBS system was more accurate for the humans when derived from human data, but the pig data predicted the pig PMIs equally as well. Overall, estimations of PMI from TBS were not highly accurate for either species. Examining the dynamic linear regressions for both species showed that it was possible to construct a model from pig data that would accurately predict pig decomposition as measured by TBS. The same situation is true for humans: a model constructed from human TBS data could accurately predict future human TBS values. However when the model built from pig data was used to forecast human values, the predictive power was lower. This issue of prediction failure was highlighted by identifying that the actual human values and the predicted pig values did not have a linear relationship to each other. Even though the Spearman's correlation coefficient seemed to indicate that there was a close relationship between the two data sets, the lack of a linear relationship renders the correlations invalid.

The hypotheses concerning insect activity were supported to varying degrees. Insects did not vary significantly by species type or by length of presence of insects. Locations of larval masses did differ between the two species. The lack of insect species differentiation between carrion type reflects the results of earlier studies (e.g. Schoenly et al., 2007). The data collected in this project supports the suggestion that season and geography are the primary drivers of species diversity for forensically significant insect taxa (Greenberg and Kunich, 2002, Farrell et al., 2015).

It is important to note that previous studies comparing insect activity on pig and human remains did not address how the location of larval masses could impact decomposition progression or scoring. This research shows that even in situations of rapid decomposition, such as during the warmest months of Trial 2 Summer, the overall pattern and corresponding TBS scores can differ between pigs and humans. The larval masses on the pigs frequently started in the mouth and under the tail, and quickly joined into one large mass that covered the entire body. In the humans the most common pattern was one of multiple smaller masses constrained to the face, groin, or axillae. Some continuous larval movement may have occurred along the dorsal surface of the human remains where the body came into contact with the ground, but this was not able to be visually observed nor did it affect the assigned TBS score.

The final hypothesis that humans would be more likely to be scavenged by raccoons was well supported. Humans were scavenged in every trial, while pigs were only scavenged in Trial 3 Winter. In addition, the pigs in Trial 3 Winter were not scavenged until after all of the humans had already been impacted by raccoon activity. The preferential scavenging of humans in each trial demonstrates the need for examining all factors that can affect the rate of decomposition when attempting to better assess decomposition as a complex process. Human remains that were scavenged often had bone exposure much earlier in the data collection period and therefore also had correspondingly higher TBS scores. This project did not investigate the cause for preferential scavenging of the humans as compared to the pigs, nor did it attempt to explain why certain humans were scavenged more heavily than others. Attempting to discern why some humans were clearly preferred by scavengers would be an excellent avenue for continuing research.

Future directions of research

This research has the primary goal of determining if domestic pigs are similar to humans, and if so, evaluate if the two species are similar enough for pigs to act as a direct substitute for human remains in decomposition research. This question is very broad, and the project discussed here has only begun to provide answers. At a minimum, this study needs to be repeated to evaluate and validate the conclusions drawn from this research. In addition, several other areas for expansion have been identified through the course of this work.

Differences between decomposition were identified between domestic pigs and humans. In addition to assessing these differences on a broad morphological scale, another area to directly compare pigs and humans is with microbial data. Expansions of the studies by Parkinson (2009) and Metcalf (2016) to further examine what the extent of the variability is in humans for a given microenvironment is needed. It would also be beneficial to assess if there exists variation in pig microbial communities as well, and question if this variation overlaps. This is an important variable to further investigate as distinct differences in scavenger preference were observed between sets of human remains. Understanding microbial variation in humans (and its relationship to other decomposition variables) could allow for better predictive ability in model building. While it may not always be possible to easily or inexpensively analyze microbial content of remains in forensic situations, the data produced from research contexts could still help investigators more accurately interpret what they are seeing if the contribution of the microbes is better understood.

Another factor identified during this research is the effect of applying a scoring system based on human decomposition to pig remains. While there is a modification of the TBS system available for research contexts, it presents a new challenge of then potentially applying a system intended for pigs onto human remains (Keough et al., 2017). An alternative option would be to

choose or design another system to objectively identify decomposition progression, regardless of species. A less biased way of evaluating morphological indicators that does not force researchers to choose from a set list of options. A system that is based on presence or absence of indicators may be easier to effectively implement on both species. Ideally the system would be developed on both pigs and humans observed in person and in photographs to be applicable to the maximum number of research contexts. As there are multiple decomposition research facilities that work with either pig or human remains, or both, it should be feasible to gather a large amount of data for development of new scoring methods.

Given the sensitivity to initial conditions, more complete medical histories of human donors would be beneficial. Although initial conditions are neither known nor inferred in forensic cases, research with donated remains provides a unique opportunity to study decomposition with as many variables identified as possible. Having detailed information on diet, illness, medication and lifestyle attributes may provide critical insight to the morphological indicators, insect activity patterns and scavenging behavior observed. This again relates to the distinct differences observed in scavenging behaviors not only between the two species, but within them as well. This is not the first study to identify preferential scavenging of human donors (Smith, 2015, Synstelein, 2017). There may be consistent patterns to the scavenging behavior that have not yet been identified because the initial conditions have not been fully explained or documented. Again, a research context provides a unique opportunity to provide in-depth analyses that cannot be constructed in the case of forensic contexts. Even when scavenging is not taken into account the human donors from each trial did not have identical daily TBS scores. This indicates that factors other than time, temperature, season or insect activity are contributing to the variation observed in decomposition progression.

If pigs are going to continue to be used in taphonomic studies, it may help to attempt to increase variation in pigs. Animals can be purchased from different farms within the same state, across states, or different farming practices (e.g. conventional versus organic, or commercial versus small family owned). Intentionally sourcing the pigs from different locations and farmers may better replicate the variation that can be seen in humans. Increased variation in pigs will complicate interpretation of results, but again provides unique insight with known initial conditions. During all three trials, the pigs used in this research had more similar daily TBS scores to each other than the humans had to each other. This indicates that some unobserved variables are being held more consistent among the pigs than among the humans. Intentionally increasing the variation among the pigs allows to test hypotheses about the role of diet or geographical origin without having to alter any other variable.

A common refrain in decomposition studies is the need for increased sample size. In addition to repeating this study at the ARF, expanding this study to include other research facilities in the United States and abroad would help to evaluate if the results observed in this dissertation are applicable to other geographical areas and climates. Tennessee has weather patterns that include steep increases or decreases in temperature within a single day. Animal and insect species also vary by location, and the behaviors and patterns observed in east Tennessee will not necessarily apply to all climates. While this study was the first to systematically address decomposition differences between humans and domestic pigs across multiple seasons, it did not investigate all seasons. Autumn in Tennessee has fluctuating temperatures that vary as much as spring temperatures, but in different patterns. Repeating this study at the ARF should include autumn trials as well. Seasonality was identified as a key component of decomposition progression variation, and so should be included in any future study conducted in any location.

Results of this dissertation suggest that there is a difference in decomposition progression between pigs and humans, but does not attempt to address how to correct for that. With more data on each season, it may be possible to uncover a pattern of error from the pig models and develop an adjustment that would allow pig remains to be used in more taphonomic studies. In order to accomplish this goal, multiple trials from each season would need to be completed. Developing a correction factor that can be uniformly applied to even one ecological context would need to be grounded in a huge amount of data to ensure that the patterns identified are consistent and that the correction factor successfully decreases error. Another approach that will help to elucidate the error is applying a jackknife method to the time series statistics. This method will remove one individual at a time from the group assessment, and will further minimize any influence of outlier observations.

Conclusions

Decomposition research has frequently taken a Newtonian approach, focusing on isolating a single aspect or variable to understand its contribution to the rate of the decomposition process. As the field moves forward, a systems approach which emphasizes the complex and interactive nature of decomposition will provide the best option for improving time since death estimates. While the use of domestic pigs as a proxy for human remains may be suitable for examining individual variables, overall the patterns of decomposition are not similar enough to rely on the data from an animal model alone. Taphonomic research should not use an animal model as a substitute for human remains with the intent to apply the resulting data to human forensic contexts without directly comparing the variable of interest to both species. Assumptions that because humans and pigs are similar in some respects means that they are similar in all respects must be challenged in order for the field to progress.

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Appendices

Appendix A: TBS data

Daily TBS of all subjects in Trial 1 Spring.

	Humans					Pigs				
Date	112	113	114	115	116	107	108	109	110	111
3/14/2014	3	3	3	3	3	3	3	3	3	3
3/15/2014	6	6.5	8	3.5	7	3	3	3	3	3
3/16/2014	7	6	6.5	5	7	6	5	6.5	6	6.5
3/17/2014	8	6.5	9	7	8	7	6.5	8	7	7
3/18/2014	8	8	10	8	8	9	7.5	9	8.5	8.5
3/19/2014	8	8.5	10	8	8	9	9	9	8.5	9
3/20/2014	8	9	10	8.5	8	9	9	9	8.5	8.5
3/21/2014	8	9	10	9	9	9	9	9	9	9
3/22/2014	9	9	10	9	9	9	9	9	9	9
3/23/2014	9	9	10	9	9	9	10	9	9	9
3/24/2014	12	10	11	10	10	10	10	10	10	9
3/25/2014	13	11	11	10	10	10	10	10	10	10
3/26/2014	13	10	10	10	10	10	10	10	10	10
3/27/2014	13	11	11	10	11	10	13	10	10	10.5
3/28/2014	12.5	10	11	10	11.5	11	13	13	13	13
3/30/2014	14	10	12	12	12	12	13	13	13	11.5
3/31/2014	14	12	12	12	12	13	13	13	13	13
4/1/2014	14	12	11	12	14	13	13	13	13	13
4/2/2014	14	12	12.5	11.5	14.5	12.5	13	12.5	12.5	12.5
4/3/2014	14	13	11	11.5	14.5	12	12	12	12	12
4/4/2014	15	13	14	13	14.5	13	12	12	12	12
4/5/2014	14	12.5	13.5	13	14.5	13	12.5	12	12.5	12.5
4/6/2014	15	14	13	12.5	15	13	13	13	13	13
4/7/2014	14	13	13	12	13	13	13	13	13	13
4/8/2014	15.5	13	13.5	12.5	16	14.5	13	13	13.5	13.5
4/9/2014	15	14	13	13	16	13.5	13	13	13	13.5
4/10/2014	16	12	14	13	13	13	12	12	13	13
4/11/2014	16	13	14	14	14.5	13.5	13.5	13.5	13.5	13
4/12/2014	16	15	14	14	15	15	13.5	13	14	14
4/13/2014	19	16	14	14	16	15.5	15	15	17	17
4/14/2014	17	16	15	14	17	17	18	16	17	17
4/16/2014	15	17	16	14.5	18.5	17	17	17	17	17
4/17/2014	16	17	15	15	18	17	17	16	17	17
4/18/2014	16	17	14.5	14	19.5	17	17	17	17	18
4/19/2014	16	17	15	15	19	18	17	16	17	18
4/20/2014	16	18	16	15	20	17.5	17	17	18	18
4/21/2014	16	17.5	17	14.5	21	17	17	17	17	18

Date	Humans					Pigs				
4/22/2014	16	22	17	15	22	18	17	18	19	18
4/23/2014	18	22	20	18	22	18	18	18	19	18
4/24/2014	17	22	16	16	22	18	18	18	19	18
4/25/2014	19	22	20	18	22	18	18	18	19	19
4/26/2014	16	21	17	14	21	17	17	17	17	18
4/27/2014	16	23	16	15	19	17	13	17	19	16
4/28/2014	19	23	20	18	22	18	18	18	19	19
4/30/2014	17	21	20	15	21	18	18	17	18	18
5/1/2014	17	21	20	18	21	18	18	18	19	18
5/2/2014	17	21	20	18	22	18	18	18	20	18
5/3/2014	17	21	20	18	22	18	18	18	20	19
5/4/2014	20	23	23	19	24	19	18	20	25	20
5/5/2014	17	22	20	18	23	18	18	18	20	21
5/6/2014	20	23	21	19	23	18	18	18	25	21
5/7/2014	20	25	21	19	23	20	18	18	26	21
5/8/2014	19	22	21	18	23	18	18	18	23	21
5/9/2014	20	24	21	19	23	18	18	18	26	21
5/10/2014	20	24	21	19	23	18	18	18	27	24
5/11/2014	20	22	21	20	22	18	18	18	25	21
5/12/2014	20	22	21	20	22	18	18	18	25	22
5/13/2014	20	22	22	20	23	18	18	18	26	22
5/14/2014	20	23	22	20	24	18	18	19	22	22
5/16/2014	20	22	22	20	24	18	19	20	24	22
5/17/2014	21	26	22	20	24	18	19	20	25	23
5/18/2014	21	25	22	20	24	18	18	20	25	23
5/19/2014	20	24	21	20	24	18	20	20	27	22
5/21/2014	21	26	21	20	24	21	26	21	27	23
5/25/2014	21	26	22	20	24	22	21	21	27	25
5/27/2014	21	26	23	20	24	22	23	23	27	24

Daily TBS of all subjects in Trial 2 Summer.

	Humans					Pigs				
Date	117	118	119	120	121	122	123	124	125	126
6/14/2014	3	3	3	4	3.5	3	3	3	3	3
6/15/2014	4.5	5	3	8.5	6	3	3.5	4	3	3
6/16/2014	12.5	12	12	14.5	14.5	12	8	12	7	6
6/17/2014	14.5	11.5	12.5	16	17	16	17.5	16	15.5	11
6/18/2014	15	14	19	18	21	17.5	20	19	18.5	13
6/19/2014	16	14	17	16	25	21	20.5	27	20	15
6/20/2014	17.5	15	21	18	25	24.5	25	28	23.5	20.5
6/21/2014	17.5	18.5	22.5	19	28	28.5	28	29	25	27
6/22/2014	20.5	22.5	22.5	21	29	26	29	31	27.5	29
6/23/2014	21.5	22	24.5	20	28	28	29	30	26.5	29
6/24/2014	20	19.5	21	21	23.5	25.5	26.5	28	26	27.5
6/25/2014	19	19	21	21	23	23	21	25	23	25
6/26/2014	21.5	21.5	23.5	23	28.5	28	27.5	30	28	29
6/27/2014	23	21	23	22	28	29	27	30	28	30
6/28/2014	22	22	24	24	27	30	28	30	27	30
6/29/2014	24	23	24	26	27	30	28	30	27	30
6/30/2014	24	24	24	26	27	30	28	30	28	30
7/1/2014	24	24	24	24	29	30	29	30	28	29
7/2/2014	24	25	24	24	29	30	29	30	28	29
7/3/2014	24	25	24	24	29	30	29	30	28	29
7/4/2014	24	25	24	24	29	30	29	30	28	29
7/5/2014	24	25	24	24	30	30	29	30	28	29
7/6/2014	24	25	24	24	30	30	29	30	28	29
7/7/2014	24	25	24	24	30	30	29	30	28	29
7/8/2014	24	25	24	26	30	30	29	30	28	29
7/9/2014	24	25	24	26	30	30	29	30	28	29
7/10/2014	24	25	24	26	31	30	30	31	28	30
7/11/2014	24	25	24	26	31	30	30	31	28	30
7/12/2014	24	25	24	26	31	30	30	31	28	30
7/13/2014	24	25	24	26	31	30	30	31	28	30
7/14/2014	24	25	24	26	31	30	30	31	28	30
7/15/2014	24	25	24	26	31	30	30	31	28	30
7/16/2014	24	25	24	26	31	32	30	32	28	30
7/17/2014	24	25	24	26	31	32	30	32	28	30

Daily TBS for all subjects in Trial 3 Winter.

	Humans					Pigs				
Date	142	143	144	145	146	132	133	134	135	136
12/1/2014	3	3	3	3	3	3	3	3	3	3
12/2/2014	6.5	8	4	6	6	4.5	4.5	3.5	5	4.5
12/3/2014	6.5	8	4	6	6	5	4	5	5	5
12/4/2014	7.5	8.5	6	6	7	5	5	5	5	5
12/5/2014	8	9	6.5	7	7	6	6	5	6.5	5.5
12/6/2014	7	8	4	6	6	5	4	3	5	4
12/7/2014	8	8	6.5	7	7	5	7	5	7	5
12/8/2014	8	8	7	7	7.5	6	6.5	4	7	5.5
12/9/2014	8	9	7	7	8	6	7	4	7	6
12/10/2014	9	9	7	8	8	7	7	6	7.5	7
12/11/2014	9	9.5	7	8	8.5	8	9	6.5	8	6.5
12/12/2014	9	9	8	8.5	10	8	9	8	8	7
12/13/2014	10	10	9	10	10	9	10	7	8	8
12/14/2014	11	10	9	10	10.5	10	10	7	8	8
12/15/2014	10	10	8	9	9	8	9	8	9	8
12/16/2014	9	10	8	9.5	9.5	9	8.5	7	9	9
12/17/2014	10	10	9	10	9	9	9	9	9	9
12/18/2014	9	10	8	9	9	9	11	9	9	9
12/19/2014	10	9	9	9	9	10	10	9	9	10
12/20/2014	9	10	8	9	9	10	10	9	10	10
12/21/2014	10	10	9	10	10	10	10	10	10	10
12/22/2014	10	10	9	10	10	10	10	10	10	10
12/23/2014	10	10	9	10	10	10	10	10	10	10
12/24/2014	10	10	10	10	10	10	10	10	10	10
12/25/2014	10	11	10	10	10	10	10	10	10	10
12/26/2014	10	10.5	9.5	10	10	10	10	10	10	10
12/27/2014	10	11	10	10	10	10	10	10	10	10
12/28/2014	10	11	10	10	10	11	10	11	10	10
12/29/2014	10	12	10	10	10	10	11	11	10	10
12/30/2014	11	12	11	10	11	12	10	12	11	11
12/31/2014	12	13	11	12	13	13	13	12	11	11
1/1/2015	12	13	11	10	12	12	12	12	10	11
1/2/2015	14	13	11	10	12	12	12	12	12	11
1/3/2015	14	13	11	13	13	12	12	12	12	12
1/4/2015	12	14	11	12	12	12	12	12	12	12.5
1/5/2015	12	14	11	12	12	13	13	13	12	13
1/6/2015	14	14	12	13	14	13	13	13	13	13
Date	Humans					Pigs				

1/7/2015	14	14	12	14	14	13	13	13	13	13
1/8/2015	14	14	12	14	14	13	13	13	13	13
1/9/2015	14	14	12	14	14	13	13	13	13	13
1/10/2015	14	14	12	14	14	13	13	13	13	13
1/11/2015	14	14	12	14	14	13	13	13	13	13
1/13/2015	13	13	12	13	13	13	13	13	13	13
1/14/2015	13	14	12	13	13	13	13	13	13	13
1/15/2015	13	14	12	12	13	13	13	13	13	13
1/16/2015	13	14	12	13	13	13	13	13	13	13
1/17/2015	13	14	12	13	13	13	13	13	13	13
1/18/2015	13	14	12	13	13	13	13	13	13	13
1/19/2015	13	14	12	13	13	13	13	13	13	13
1/20/2015	13	14	12	13	13	13	13	13	13	13
1/21/2015	13	14	12	13	13	13	13	13	13	13
1/22/2015	13	14	12	13	13	13	13	13	13	13
1/24/2015	13	14	13	12	13	13	13	13	13	13
1/25/2015	13	14	12	12	13	13	13	13	13	13
1/26/2015	13	14	12	16	13	13	13	13	13	13
1/27/2015	13	14	12	12	13	13	13	13	13	13
1/29/2015	13	14	12	16	13	13	13	13	13	13
1/30/2015	14	14	12	12	13	13	13	13	13	13
1/31/2015	13	14	12	13	13	13	13	13	13	13
2/3/2015	13	14	14	27	16	13	13	13	13	13
2/4/2015	13	18	24	29	18	13	13	13	13	13
2/7/2015	13	15	17	27	13	13	13	13	13	13
2/8/2015	13	15	13	27	13	13	13	13	13	13
2/9/2015	14	15	13	27	13	13	13	13	13	13
2/10/2015	14	15	13	27	13	13	13	13	13	13
2/12/2015	14	15	13	27	13	13	13	13	13	13
2/13/2015	14	15	13	27	13	13	13	13	13	13
2/14/2015	16	17	24	28	24	14	13	19	14	15
2/16/2015	16	17	24	28	24	14	13	19	14	15
2/23/2015	14	15	13	27	15	14	13	19	14	15
3/3/2015	14	15	13	27	13	13	13	13	13	13
3/4/2015	14	15	13	27	13	13	13	13	13	13
3/8/2015	23	21	24	29	24	15	20	20	15	15
3/9/2015	22	24	24	28	22	14	21	17	14	11
3/12/2015	23	23	24	29	24	14	18	17	13	13
3/15/2015	23	18	24	27	24	13	18	18	13	13
3/16/2015	23	19	24	28	23	13	18	18	13	13
Date	Humans					Pigs				

3/17/2015	23	23	24	28	24	13	18	19	13	14
3/18/2015	23	23	24	28	24	13	18	18	14	15
3/21/2015	23	23	24	28	24	13	18	18	14	15
3/22/2015	23	24	24	28	24	13	21	21	15	16

Appendix B: SAS code (SAS version 9.4) for HLM and Time Series Models

HLM for all trials

```
/*  
  
%include 'c:\danda.sas';  
%include 'c:\assumptions.sas';  
%include 'c:\boxcox.sas';  
%include 'c:\transform.sas';  
*/  
  
proc import datafile="H:\My Documents\My SAS Files\9.4\HLM.xlsx"  
    out=work.all  
    dbms=xlsx  
    replace;  
run;  
proc print data=all;  
run;  
data winter;  
    set all;  
    where season="Winter";  
run;  
/* VIFs */  
Title 'Variance Inflation Factors';  
proc reg data=Winter;  
model Head = Treatment2 Time Temp /vif dw;  
run;  
quit;  
/* VIFs */  
Title 'Variance Inflation Factors';
```

```

proc reg data=Winter;
model Head = Treatment2 Time Scavenging Temp /vif dw;
run;
quit;

proc reg data=Winter;
model Trunk = Treatment2 Time Scavenging Temp /vif dw;
run;
quit;

proc reg data=Winter;
model Limbs = Treatment2 Time Scavenging Temp /vif dw;
run;
quit;

proc reg data=Winter;
model TBS= Treatment2 Time Scavenging Temp /vif dw;
run;
quit;

Title 'Winter HLM - Head';

proc glimmix data=Winter plots=all maxopt=1000;
class Subject Treatment Season;
model Head = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;

Title 'Winter HLM - Trunk';

proc glimmix data=Winter plots=all maxopt=1000;
class Subject Treatment Season;
model Trunk = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;

```



```

lsmeans Treatment;
run;
Title 'Winter HLM - Limbs';
proc glimmix data=Winter plots=all maxopt=1000;
class Subject Treatment Season;
model Limbs = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;
Title 'Stepwise Correction on HLM';
data winter2;
input effect$ Raw_P @@;
datalines;
treat 0.0115 time 0.0001
scav 0.1417 temp 0.0151
;
proc multtest inpvalues=winter2 holm hoc fdr;
run;
data spring;
    set all;
    where season="Spring";
run;
Title 'Spring HLM - Head';
proc glimmix data=spring plots=all maxopt=1000;
class Subject Treatment Season;
model Head = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;

```

```

run;
Title 'Spring HLM - Trunk';
proc glimmix data=spring plots=all maxopt=1000;
class Subject Treatment Season;
model Trunk = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;
Title 'Spring HLM - Limbs';
proc glimmix data=spring plots=all maxopt=1000;
class Subject Treatment Season;
model Limbs = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;
Title 'Stepwise Correction on HLM';
data spring2;
input effect$ Raw_P @@;
datalines;
treat 0.0987 time 0.0001
scav 0.0642 temp 0.0172
;
proc multtest inpvalues=spring2 holm hoc fdr;
run;
data summer;
    set all;
    where season="Summer";
run;

```

```
Title 'Summer HLM - Head';
proc glimmix data=summer plots=all maxopt=1000;
class Subject Treatment Season;
model Head = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;
```

```
Title 'Summer HLM - Trunk';
proc glimmix data=summer plots=all maxopt=1000;
class Subject Treatment Season;
model Trunk = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;
```

```
Title 'Summer HLM - Limbs';
proc glimmix data=summer plots=all maxopt=1000;
class Subject Treatment Season;
model Limbs = Treatment Time Scavenging Temp /solution;
random int time temp /subject=Subject type=vc;
lsmeans Treatment;
run;
```

```
Title 'Stepwise Correction on HLM';
data summer2;
input effect$ Raw_P @@;
datalines;
treat 0.3172 time 0.0002
scav 0.2026 temp 0.4308
;
```

```
proc multtest inpvalues=summer2 holm hoc fdr;
run;
```

Dynamic linear regression models

```
/******Summer Models******/
```

```
title;
```

```
proc import datafile='C:\Dropbox\Clients\adautart\Time Series\SummerHO.xlsx'
```

```
  out=work.SummerHO
```

```
  dbms=xlsx
```

```
  replace;
```

```
run;
```

```
proc import datafile='C:\Dropbox\Clients\adautart\Time Series\Summer.xlsx'
```

```
  out=work.Summer
```

```
  dbms=xlsx
```

```
  replace;
```

```
run;
```

```
proc print data=Summer;
```

```
run;
```

```
proc print data=SummerHO;
```

```
run;
```

```
Title 'Pig Forecasts for Summer - Holdout Sample';
```

```
proc arima data=SummerHO plots(unpack)=all out=out;
```

```
identify var=TBSP crosscorr=(ScavengingP BugsP Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);
```

```
/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */
```

```

estimate p=(1)(0) q=(3)(0) Maxiter=32000 singular=1E-9 input=(ScavengingP BugsP Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=4 out=work.out2;

/* lead=forecast horizon */

run;

quit;

Title 'Human Forecasts for Summer - Holdout Sample';

proc arima data=SummerHO plots(unpack)=all;

identify var=TBSH crosscorr=(ScavengingH BugsH Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(1)(0) q=(3)(0) Maxiter=32000 singular=1E-9 input=(ScavengingH BugsH Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=4 out=work.out2;

/* lead=forecast horizon */

run;

quit;

Title 'Pig Forecasts for Summer';

proc arima data=Summer plots(unpack)=all;

identify var=TBSP crosscorr=(ScavengingP BugsP Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

```

```

estimate p=(1)(0) q=(3)(0) Maxiter=32000 singular=1E-9 input=(ScavengingP BugsP Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=0 out=work.out;

/* lead=forecast horizon */

run;

quit;

Title 'Human Forecasts for Summer';

proc arima data=Summer plots(unpack)=all;

identify var=TBSH crosscorr=(ScavengingH BugsH Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(1)(0) q=(3)(0) Maxiter=32000 singular=1E-9 input=(ScavengingH BugsH Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;
      /* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=0 out=work.out;

/* lead=forecast horizon */

run;

quit

data corrddata;

      set work.out;

      set work.Summer;

run;

proc univariate data=corrddata normal;

var TBSH FORECAST;

probplot;

```

```

run;
Title' Summer Correlation values for Human vs Predicted Pig';
proc corr data=corrdata pearson spearman;
var TBSH FORECAST;
run;
proc glm data=corrdata plots=all;
model TBSH = Forecast Forecast*Forecast/solution;
run;
quit;

/*****Spring Models*****/
proc import datafile='C:\Dropbox\Clients\adautart\Time Series\SpringHO.xlsx'
    out=work.SpringHO
    dbms=xlsx
    replace;
run;
proc import datafile='C:\Dropbox\Clients\adautart\Time Series\Spring.xlsx'
    out=work.Spring
    dbms=xlsx
    replace;
run;
proc print data=Spring;
run;
proc print data=SpringHO;
run;
Title 'Pig Forecasts for Spring - Holdout Sample';
proc arima data=SpringHO plots(unpack)=all;

```

```

identify var=TBSP crosscorr=(ScavengingP BugsP Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(1)(0) q=(3)(0) Maxiter=32000 singular=1E-9 input=(ScavengingP BugsP Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=7 out=work.out2;

/* lead=forecast horizon */

run;

quit;

Title 'Human Forecasts for Spring - Holdout Sample';

proc arima data=SpringHO plots(unpack)=all;

identify var=TBSP crosscorr=(ScavengingH BugsH Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(1)(0) q=(0)(7) Maxiter=32000 singular=1E-9 input=(ScavengingH BugsH Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic
regressors */

forecast Lead=7 out=work.out2;

/* lead=forecast horizon */

run;

quit;

Title 'Pig Forecasts for Spring';

proc arima data=Spring plots(unpack)=all out=work.out3;

```



```

identify var=TBSP crosscorr=(ScavengingP BugsP Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(1)(0) q=(3)(0) Maxiter=32000 singular=1E-9 input=(ScavengingP BugsP Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=0;

/* lead=forecast horizon */

run;

quit;

Title 'Human Forecasts for Spring';

proc arima data=Spring plots(unpack)=all;

identify var=TBSP crosscorr=(ScavengingH BugsH Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(1)(0) q=(0)(7) Maxiter=32000 singular=1E-9 input=(ScavengingH BugsH Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=0;

/* lead=forecast horizon */

run;

quit;

data corrrdata;

    set work.out3;

```

```

        set work.Spring;

run;

proc univariate data=corrdata normal;
var TBSH FORECAST;
probplot;
run;

Title' Summer Correlation values for Human vs Predicted Pig';

proc corr data=corrdata pearson spearman plots=all;
var TBSH FORECAST;
run;

proc glm data=corrdata plots=all;
model TBSH = Forecast /solution;
run;
quit;

/*****Winter Models*****/

proc import datafile='C:\Dropbox\Clients\adautart\Time Series\WinterHO.xlsx'
    out=work.WinterHO
    dbms=xlsx
    replace;
run;

proc import datafile='C:\Dropbox\Clients\adautart\Time Series\Winter.xlsx'
    out=work.Winter
    dbms=xlsx
    replace;
run;

proc print data=Winter;
run;

```

```
proc print data=WinterHO;
```

```
run;
```

```
Title 'Pig Forecasts for Winter - Holdout Sample';
```

```
proc arima data=WinterHO plots(unpack)=all;
```

```
identify var=TBSP(2) crosscorr=(ScavengingP BugsP Trend Temperature DaySeason_1  
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7  
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);
```

```
/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in  
order to add in dynamic regressors */
```

```
estimate p=(2)(0) q=(2)(0) Maxiter=32000 singular=1E-9 input=(ScavengingP BugsP Trend  
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5  
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4  
WeekSeason_5) WHITENOISE=ST;
```

```
/* Use the input=(var1 var2 option here in order to add in dynamic regressors */
```

```
forecast Lead=7 out=work.out2;
```

```
/* lead=forecast horizon */
```

```
run;
```

```
quit;
```

```
Title 'Human Forecasts for Winter - Holdout Sample';
```

```
proc arima data=WinterHO plots(unpack)=all;
```

```
identify var=TBSH(1) crosscorr=(ScavengingH BugsH Trend Temperature DaySeason_1  
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7  
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);
```

```
/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in  
order to add in dynamic regressors */
```

```
estimate p=(0)(0) q=(4)(0) Maxiter=32000 singular=1E-9 input=(ScavengingH BugsH Trend  
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5  
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4  
WeekSeason_5) WHITENOISE=ST;
```

```
/* Use the input=(var1 var2 option here in order to add in dynamic  
regressors */
```

```

forecast Lead=7 out=work.out2;

/* lead=forecast horizon */

run;

quit;

Title 'Pig Forecasts for Winter';

proc arima data=Winter plots(unpack)=all out=work.out6;

identify var=TBSP(2) crosscorr=(ScavengingP BugsP Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(2)(0) q=(2)(0) Maxiter=32000 singular=1E-9 input=(ScavengingP BugsP Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

/* Use the input=(var1 var2 option here in order to add in dynamic regressors */

forecast Lead=0;

/* lead=forecast horizon */

run;

quit;

Title 'Human Forecasts for Winter';

proc arima data=Winter plots(unpack)=all;

identify var=TBSH(1) crosscorr=(ScavengingH BugsH Trend Temperature DaySeason_1
DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5 DaySeason_6 DaySeason_7
WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4 WeekSeason_5);

/* Differencing is applied to this line var=y (d D). Use the crosscorr=(var1 var2) option here in
order to add in dynamic regressors */

estimate p=(0)(0) q=(4)(0) Maxiter=32000 singular=1E-9 input=(ScavengingH BugsH Trend
Temperature DaySeason_1 DaySeason_2 DaySeason_3 DaySeason_4 DaySeason_5
DaySeason_6 DaySeason_7 WeekSeason_1 WeekSeason_2 WeekSeason_3 WeekSeason_4
WeekSeason_5) WHITENOISE=ST;

```

```

/* Use the input=(var1 var2 option here in order to add in dynamic
regressors */
forecast Lead=0;

/* lead=forecast horizon */
run;
quit;
data corrrdata;
    set work.out6;
    set work.Winter;
run;
proc univariate data=corrrdata normal;
var TBSP FORECAST;
probplot;
run;
Title' WinterCorrelation values for Human vs Predicted Pig';
proc corr data=corrrdata pearson spearman plots=all;
var TBSP FORECAST;
run;
proc glm data=corrrdata plots=all;
model TBSP = Forecast Forecast*Forecast Forecast*Forecast*Forecast /solution;
run;
quit;
proc glm data=corrrdata plots=all;
model TBSP = TBSP TBSP*TBSP TBSP*TBSP*TBSP /solution;
run;
quit;

```

Appendix C: Full reports for dynamic linear regression models

Trial 1

Pig Forecasts for Spring - Holdout Sample

The ARIMA Procedure

Name of Variable = TBSP	
Mean of Working Series	15.14 118
Standard Deviation	4.661 805
Number of Observations	68

Autocorrelation Check for White Noise									
To Lag	Chi- Squar e	D F	Pr > ChiSq	Autocorrelation s					
6	266.83	6	<.0001	0.919	0.842	0.788	0.735	0.694	0.662
12	402.43	12	<.0001	0.624	0.587	0.546	0.503	0.462	0.424

Conditional Least Squares Estimation							
Para meter	Estim ate	Stan dard Er ror	t Val ue	App rox Pr > t	L ag	Variable	Sh ift
MU	2.46334	1.24006	1.99	0.0526	0	TBSP	0
MA1, 1	-0.16189 0.28621		-1.77	0.0833	3	TBSP	0
AR1,	0.968	0.054	17.6	<.00	1	TBSP	0

1	72	96	2	01			
NUM 1	0	0	.	.	0	Scavengi ngP	0
NUM 2	- 0.207 55	0.330 83	- 0.63	0.53 33	0	BugsP	0
NUM 3	0.282 39	0.093 09	3.03	0.00 39	0	Trend	0
NUM 4	- 0.005 7431	0.032 89	- 0.17	0.86 21	0	Tempera ture	0
NUM 5	- 0.491 29	0.300 06	- 1.64	0.10 80	0	DaySeas on_1	0
NUM 6	- 0.402 25	0.353 26	- 1.14	0.26 04	0	DaySeas on_2	0
NUM 7	- 0.212 42	0.321 79	- 0.66	0.51 23	0	DaySeas on_3	0
NUM 8	- 0.787 39	0.316 45	- 2.49	0.01 63	0	DaySeas on_4	0
NUM 9	- 0.914 15	0.316 41	- 2.89	0.00 57	0	DaySeas on_5	0
NUM 10	- 0.512 64	0.253 10	- 2.03	0.04 83	0	DaySeas on_6	0
NUM 11	- 0.634 48	0	- Inf ty	<.00 01	0	DaySeas on_7	0
NUM 12	- 0.169 04	0.785 75	- 0.22	0.83 06	0	WeekSe ason_1	0
NUM 13	0.567 68	0.905 60	0.63	0.53 37	0	WeekSe ason_2	0
NUM 14	0.807 61	0.929 78	0.87	0.38 93	0	WeekSe ason_3	0
NUM 15	1.486 26	0.878 81	1.69	0.09 71	0	WeekSe ason_4	0
NUM 16	0.382 30	0.714 80	0.53	0.59 52	0	WeekSe ason_5	0

Constant Estimate	0.077058
Variance Estimate	0.719258
Std Error Estimate	0.848091
AIC	186.2845
SBC	228.4552
Number of Residuals	68

Autocorrelation Check of Residuals									
To Lag	Chi-Square	D F	Pr > ChiSq	Autocorrelations					
6	2.304	4	0.6811	-0.099	-0.035	0.031	0.060	-0.047	0.114
12	7.750	10	0.6536	-0.146	0.025	0.057	0.051	-0.068	0.184
18	13.176	16	0.6601	-0.117	-0.072	0.124	0.156	-0.032	-0.028
24	14.912	22	0.8662	-0.020	0.060	-0.034	-0.041	0.037	-0.091

Model for variable TBSP	
Estimated Intercept	2.463336

Autoregressive Factors

Factor 1:	1 - 0.96872 B**(1)
------------------	--------------------------

Moving Average Factors	
Factor 1:	1 + 0.28621 B**(3)

Human Forecasts for Spring - Holdout Sample

The ARIMA Procedure

Name of Variable = TBSH	
Mean of Working Series	15.77 059
Standard Deviation	4.909 057
Number of Observations	68

Autocorrelation Check for White Noise									
To Lag	Chi- Square	D F	Pr > ChiSq	Autocorrelation s					
6	290.95	6	<.0001	0.921	0.875	0.827	0.779	0.745	0.706
12	447.56	12	<.0001	0.661	0.623	0.586	0.539	0.506	0.469

Conditional Least Squares Estimation							
Parameter	Estimate	Standard Error	t Value	Approx Pr > t	Label	Variable	Shift
MU	2.79391	1.34669	2.07	0.0433	0	TBSH	0
MA1, 1	0.33623	0.16410	2.05	0.0458	7	TBSH	0
AR1, 1	0.98319	0.05756	17.08	<.0001	1	TBSH	0
NUM 1	-0.02412	0.32074	-0.08	0.9404	0	ScavengingH	0
NUM 2	0.61727	0.28617	2.16	0.0359	0	BugsH	0
NUM 3	0.29069	0.10725	2.71	0.0092	0	Trend	0
NUM 4	-0.01905	0.03782	-0.50	0.6166	0	Temperature	0
NUM 5	-0.41010	0.25535	-1.61	0.1147	0	DaySeason_1	0
NUM 6	-0.22637	0.30391	-0.74	0.4599	0	DaySeason_2	0
NUM 7	0.03883	0.30803	0.13	0.9002	0	DaySeason_3	0
NUM 8	-0.09400	0.30042	-0.31	0.7557	0	DaySeason_4	0
NUM 9	-0.64896	0.25821	-2.51	0.0153	0	DaySeason_5	0
NUM 10	-0.40764	0.19365	-2.11	0.0404	0	DaySeason_6	0
NUM 11	-0.54000	0	-Inf	<.0001	0	DaySeason_7	0

NUM 12	0.27 151	0.867 85	0.31	0.7 557	0	WeekSe ason_1	0
NUM 13	0.91 385	1.059 15	0.86	0.3 924	0	WeekSe ason_2	0
NUM 14	0.56 175	1.036 25	0.54	0.5 902	0	WeekSe ason_3	0
NUM 15	0.32 930	0.974 34	0.34	0.7 368	0	WeekSe ason_4	0
NUM 16	0.01 208	0.835 75	0.01	0.9 885	0	WeekSe ason_5	0

Constant Estimate	0.046 975
Variance Estimate	0.865 048
Std Error Estimate	0.930 079
AIC	198.8 349
SBC	241.0 055
Number of Residuals	68

Autocorrelation Check of Residuals									
To Lag	Chi- Squar e	D F	Pr > ChiSq	Autocorrelations					
6	5.25	4	0.2626	- 0.1 87	- 0.0 59	0.1 30	- 0.0 56	0.1 11	0.0 38
12	11.32	10	0.3334	0.0 29	0.0 47	0.2 25	- 0.0 78	0.1 05	0.0 62
18	18.10	16	0.3180	- 0.2 06	- 0.0 34	0.0 91	0.0 38	0.0 71	- 0.1 32
24	24.14	22	0.3397	0.0 60	0.1 17	- 0.1 38	- 0.0 91	- 0.0 69	0.0 98

Model for variable TBSH	
Estimated Intercept	2.79391

Autoregressive Factors	
Factor 1:	1 - 0.98319B**(1)

Moving Average Factors	
Factor 1:	1 - 0.33623B**(7)

Trial 2

The ARIMA Procedure

Name of Variable = TBSP	
Mean of Working Series	24.42581
Standard Deviation	8.458436
Number of Observations	31

Autocorrelation Check for White Noise									
To Lag	Chi-Square	D F	Pr > ChiSq	Autocorrelations					
6	55.75	6	<.0001	0.856	0.678	0.481	0.322	0.209	0.108

Conditional Least Squares Estimation							
Parameter	Estimate	Standard Error	t Value	Approx Pr > t	Lag	Variable	Shift
MU	- 5.10777	6.71243	- 0.76	0.4614	0	TBSP	0
MA1, 1	- 1.00000	0.29507	- 3.39	0.0054	3	TBSP	0
AR1, 1	0.94394	0.15699	6.01	<.0001	1	TBSP	0
NUM 1	0	0	.	.	0	ScavengingP	0
NUM 2	4.93867	3.94446	1.25	0.2344	0	BugsP	0
NUM 3	1.21980	0.88709	1.38	0.1942	0	Trend	0
NUM 4	- 0.13626	0.48046	- 0.28	0.7815	0	Temperature	0
NUM 5	- 0.55593	2.38401	- 0.23	0.8195	0	DaySeason_1	0
NUM 6	0.14922	2.85270	0.05	0.9591	0	DaySeason_2	0
NUM 7	0.69696	2.05121	0.34	0.7399	0	DaySeason_3	0
NUM 8	- 1.61637	1.63843	- 0.99	0.3433	0	DaySeason_4	0
NUM 9	- 0.51526	1.72032	- 0.30	0.7697	0	DaySeason_5	0
NUM 10	0.23571	1.37198	0.17	0.8665	0	DaySeason_6	0
NUM 11	- 0.86538	0	- Infy	<.0001	0	DaySeason_7	0

NUM 12	3.931 34	3.235 38	1.22	0.24 77	0	WeekSe ason_1	0
NUM 13	2.268 84	3.419 60	0.66	0.51 96	0	WeekSe ason_2	0
NUM 14	1.510 77	1.941 00	0.78	0.45 14	0	WeekSe ason_3	0
NUM 15	4.136 90	0	Inft y	<.00 01	0	WeekSe ason_4	0
NUM 16	4.996 55	0	Inft y	<.00 01	0	WeekSe ason_5	0

Constant Estimate	- 0.286 35
Variance Estimate	6.766 391
Std Error Estimate	2.601 229
AIC	155.8 237
SBC	183.0 695
Number of Residuals	31

Autocorrelation Check of Residuals									
To Lag	Chi- Squar e	D F	Pr > ChiSq	Autocorrelations					
6	6.134	4	0.1897	0.365	-0.107	-0.107	0.002	0.098	-0.097
12	15.730	10	0.1077	-0.260	-0.073	0.118	0.313	0.092	-0.109
18	17.726	16	0.3406	-0.079	-0.011	0.072	0.045	-0.126	-0.003
24	20.142	22	0.5741	0.025	-0.044	-0.073	-0.054	-0.049	-0.083

Model for variable TBSP

Autoregressive Factors	
Factor 1:	1 - 0.94394 B**(1)

Moving Average Factors	
Factor 1:	1 + 1 B**(3)

Human Forecasts for Summer - Holdout Sample

The ARIMA Procedure

Name of Variable = TBSH	
Mean of Working Series	21.15484
Standard Deviation	6.618539
Number of Observations	31

Autocorrelation Check for White Noise									
To Lag	Chi-Square	D F	Pr > ChiSq	Autocorrelations					
6	55.55	6	<.0001	0.81	0.63	0.45	0.35	0.27	0.20
Conditional Least Squares Estimation									

Parameter	Estimate	Standard Error	t Value	Approx Pr > t	Label	Variable	Shift
MU	- 4.94758	3.91282	- 1.26	0.2301	0	TBSH	0
MA1, 1	- 0.99999	0.64329	- 1.55	0.1460	3	TBSH	0
AR1, 1	0.94447	0.13020	7.25	<.0001	1	TBSH	0
NUM 1	5.85497	1.94925	3.00	0.0110	0	ScavengingH	0
NUM 2	1.59651	2.35232	0.68	0.5102	0	BugsH	0
NUM 3	1.07234	0.42216	2.54	0.0259	0	Trend	0
NUM 4	0.05689	0.27230	0.21	0.8380	0	Temperature	0
NUM 5	- 2.65328	1.28665	- 2.06	0.0615	0	DaySeason_1	0
NUM 6	- 1.95833	1.60362	- 1.22	0.2455	0	DaySeason_2	0
NUM 7	- 3.26413	1.06003	- 3.08	0.0096	0	DaySeason_3	0
NUM 8	- 3.14594	0.91536	- 3.44	0.0049	0	DaySeason_4	0
NUM 9	- 2.03710	1.09343	- 1.86	0.0871	0	DaySeason_5	0
NUM 10	- 1.17108	0.81716	- 1.43	0.1774	0	DaySeason_6	0
NUM 11	- 1.47231	0	- Inf	<.0001	0	DaySeason_7	0
NUM 12	2.86074	2.46060	1.16	0.2676	0	WeekSeason_1	0

NUM 13	4.06 556	2.838 04	1.43	0.1 775	0	WeekSe ason_2	0
NUM 14	4.35 338	2.062 45	2.11	0.0 565	0	WeekSe ason_3	0
NUM 15	4.55 441	1.898 84	2.40	0.0 336	0	WeekSe ason_4	0
NUM 16	4.00 345	0	Inft y	<.0 001	0	WeekSe ason_5	0
				Constant Estimate	- 0.274 72		
				Variance Estimate	2.560 471		
				Std Error Estimate	1.600 147		
				AIC	125.6 986		
				SBC	152.9 444		
				Number of Residuals	31		

Autocorrelation Check of Residuals									
To Lag	Chi- Squar e	D F	Pr > ChiSq	Autocorrelations					
6	4.45	4	0.3486	0.2 87	0.1 22	0.1 73	- 0.0 10	0.0 06	- 0.0 29
12	6.01	10	0.8148	0.0 53	0.0 45	0.1 11	0.1 12	- 0.0 48	- 0.0 26
18	8.15	16	0.9443	0.0 22	- 0.1 57	- 0.0 84	- 0.0 12	0.0 25	0.0 41
24	30.13	22	0.1153	- 0.0 48	- 0.1 24	- 0.2 63	- 0.1 12	- 0.2 09	- 0.2 06

Model for TBSH

Autoregressive Factors	
Factor 1:	1 - 0.94447 B**(1)

Moving Average Factors	
Factor 1:	1 + 0.99999 B**(3)

Trial 3

The ARIMA Procedure

Name of Variable = TBSP	
Period(s) of Differencing	2
Mean of Working Series	0.229126
Standard Deviation	0.991481
Number of Observations	103
Observation(s) eliminated by differencing	2

Autocorrelation Check for White Noise									
To Lag	Chi-Square	D F	Pr > ChiSq	Autocorrelations					
6	12.34	6	0.0547	0.199	-0.2	0.001	-0.0	-0.0	0.035

					65		52	46	
12	19.00	12	0.0884	-0.051	-0.094	0.149	0.155	0.009	-0.009
18	19.45	18	0.3648	-0.017	-0.043	-0.030	-0.014	-0.020	0.003
24	26.02	24	0.3523	0.020	0.038	0.148	0.147	-0.043	-0.048

Conditional Least Squares Estimation							
Parameter	Estimate	Standard Error	t Value	Approx Prob > t	Level	Variable	Shift
MU	0.33667	0.54150	0.62	0.5358	0	TBSH	0
MA1, 1	0.38627	0.10421	3.71	0.0004	4	TBSH	0
NUM1	-0.09689	0.41305	-0.23	0.8151	0	ScavengingH	0
NUM2	0	0	.	.	0	BugsH	0
NUM3	-0.0012067	0.0029074	-0.42	0.6792	0	Trend	0
NUM4	0.01051	0.02196	0.48	0.6334	0	Temperature	0
NUM5	0.03898	0.48277	0.08	0.9358	0	DaySeason_1	0
NUM6	-0.37300	0.48667	-0.77	0.4455	0	DaySeason_2	0
NUM7	0.54990	0.55344	0.99	0.3232	0	DaySeason_3	0
NUM8	-0.02601	0.54684	-0.05	0.9622	0	DaySeason_4	0
NUM	-	0.480	-	0.97	0	DaySeason	0

9	0.013 95	23	0.03	69	on_5	
NUM 10	- 0.477 0.159 26	67	- 0.33	0.73 96	0 DaySeas on_6	0
NUM 11	0.209 29	0	Inft y	<.00 01	0 DaySeas on_7	0
NUM 12	0.122 90	0.444 74	0.28	0.78 30	0 WeekSe ason_1	0
NUM 13	0.138 10	0.396 04	0.35	0.72 82	0 WeekSe ason_2	0
NUM 14	- 0.406 0.428 85	56	- 1.05	0.29 45	0 WeekSe ason_3	0
NUM 15	- 0.444 0.503 57	40	- 1.13	0.26 03	0 WeekSe ason_4	0
NUM 16	- 0.013 88	0	- Inft y	<.00 01	0 WeekSe ason_5	0

Constant Estimate	0.336 675
Variance Estimate	1.499 707
Std Error Estimate	1.224 625
AIC	353.5 227
SBC	401.1 217
Number of Residuals	104

Autocorrelation Check of Residuals									
To Lag	Chi- Squar e	D F	Pr > ChiSq	Autocorrelations					
6	4.10	5	0.5346	- 0.0 86	- 0.0 99	- 0.1 25	0.0 32	- 0.0 09	0.0 61
12	18.43	11	0.0721	- 0.1 01	- 0.1 01	- 0.1 01	0.1 58	- 0.0 00	0.1 38

				67	53	55		64	
18	30.99	17	0.0200	-0.015	-0.078	-0.132	0.111	0.165	-0.191
24	33.64	23	0.0706	0.057	0.048	-0.021	0.088	0.044	-0.063

Model for variable TBSP

Estimated Intercept	0.183175
Period(s) of Differencing	2

Autoregressive Factors	
Factor 1:	1 - 0.45554B**(2)

Moving Average Factors	
Factor 1:	1 - 0.95941B**(2)

**Human Forecasts for
Winter - Holdout
Sample**

The ARIMA Procedure

Name of Variable = TBSH

Period(s) of Differencing	1
Mean of Working Series	0.194231
Standard Deviation	1.239985
Number of Observations	104
Observation(s) eliminated by differencing	1

Autocorrelation Check for White Noise									
To Lag	Chi-Square	D.F	Pr > ChiSq	Autocorrelations					
6	4.956	6	0.5508	-0.024	-0.054	0.016	-0.077	0.090	0.040
12	15.932	12	0.1943	-0.052	-0.084	-0.066	0.061	-0.011	0.068
18	27.328	18	0.0732	-0.087	-0.061	-0.047	0.010	0.057	-0.081
24	30.194	24	0.1784	0.058	0.013	-0.056	0.019	-0.008	-0.025

Conditional Least Squares Estimation							
Parameter	Estimate	Standard Error	t Value	Approx Pr > t 	Lag	Variable	Shift
MU	0.30498	0.51079	0.60	0.5519	0	TBSH	0
MA1, 1	0.35853	0.09798	3.66	0.0004	4	TBSH	0
NUM	-	0.406	-	0.79	0	Scavengi	0

1	0.105 53	05	0.26	55	ngH	
NUM 2	0	0	.	.	0 BugsH	0
NUM 3	- 0.002 0.000 6168 8534	- 0.74 0.33 51			0 Trend	0
NUM 4	0.014 87	0.017 28	0.86	0.39 16	0 Tempera ture	0
NUM 5	0.024 63	0.446 66	0.06	0.95 62	0 DaySeas on_1	0
NUM 6	- 0.451 0.306 90	- 0.49 0.68 83			0 DaySeas on_2	0
NUM 7	0.529 03	0.510 59	1.04	0.30 28	0 DaySeas on_3	0
NUM 8	- 0.505 0.042 42	- 0.93 0.08 32			0 DaySeas on_4	0
NUM 9	- 0.444 0.036 75	- 0.93 0.08 43			0 DaySeas on_5	0
NUM 10	- 0.443 0.147 15	- 0.74 0.33 09			0 DaySeas on_6	0
NUM 11	0.183 68	0	Inft y	<.00 01	0 DaySeas on_7	0
NUM 12	0.117 24	0.426 11	0.28	0.78 38	0 WeekSe ason_1	0
NUM 13	0.136 73	0.383 02	0.36	0.72 19	0 WeekSe ason_2	0
NUM 14	- 0.382 0.384 49	- 0.31 1.01 74			0 WeekSe ason_3	0
NUM 15	- 0.424 0.514 70	- 0.22 1.21 86			0 WeekSe ason_4	0
NUM 16	- 0.012 18	0	- Inft y	<.00 01	0 WeekSe ason_5	0

Constant Estimate	0.304 976
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Variance Estimate	1.403535
Std Error Estimate	1.184709
AIC	368.9934
SBC	417.7649
Number of Residuals	111

Autocorrelation Check of Residuals									
To Lag	Chi-Square	D F	Pr > ChiSq	Autocorrelations					
6	4.59	5	0.4679	-0.089	-0.108	-0.126	0.022	-0.018	0.057
12	20.44	11	0.0396	-0.167	-0.125	-0.166	0.186	-0.052	0.142
18	32.85	17	0.0118	-0.041	-0.057	-0.130	0.104	0.157	-0.189
24	35.54	23	0.0460	0.061	0.053	-0.047	0.078	0.052	-0.042

Model for variable TBSH	
Estimated Intercept	0.304976
Period(s) of Differencing	1

Moving Average Factors	
Factor 1:	1 - 0.35853

	$B^{**}(4)$
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Vita

Angela Madeleine Dautartas was born in Allentown, Pennsylvania on May 17, 1983. She was raised in the Lehigh Valley and attended elementary and secondary school in the East Penn School District until the family moved to Blacksburg, Virginia in 2000. She graduated from Blacksburg High School in 2001. Angela went on to attend college at Radford University in Radford, Virginia and graduated with a B.S. in Anthropology with a minor in Forensic Studies in May of 2005. She earned her M.A. in Anthropology from the University of Tennessee in 2009. She began teaching at the college level in 2009, and has taught at four colleges. She hopes to pursue a career in anthropology focused on teaching, forensic casework, and research.