

2013

Subaerial bone weathering and other taphonomic changes in a temperate climate

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BOSTON UNIVERSITY
SCHOOL OF MEDICINE

Thesis

**SUBAERIAL BONE WEATHERING AND OTHER TAPHONOMIC CHANGES
IN A TEMPERATE CLIMATE**

by

CHRISTINE A. JUNOD

B.A., Colorado State University, 2007

Submitted in partial fulfillment of the
requirements for the degree of

Master of Science

2013

Approved by

First Reader

James T. Pokines, Ph.D., D-ABFA
Assistant Professor of Anatomy and Neurobiology
Program in Forensic Anthropology

Second Reader

Gary Reinecke, SSA ret. FBI
Instructor of Anatomy and Neurobiology
Program in Forensic Anthropology

ACKNOWLEDGEMENTS

The completion of this thesis was a group endeavor that would not have been possible without the support and advice from my thesis committee. Firstly, I would like to thank Dr. James Pokines for his invaluable feedback, suggestions, and mentoring. I would also like to thank Supervisory Special Agent Gary Reinecke, retired FBI, for his continued encouragement, useful suggestions, and for his assistance at the Holliston Outdoor Research Facility. Both Dr. Pokines and Agent Reinecke have been essential resources and I am fortunate to have them on my thesis committee.

I am also grateful to have had the support of Wildlife Program Leader Leighlan Prout at the White Mountain National Forest, and Conservation Officer Matt Holmes with the New Hampshire Fish and Game Department. Both whom have provided crucial information for data collection in the White Mountain National Forest. This portion of my thesis would not have been possible without their assistance.

I would also like to acknowledge Dr. Farzad Mortazavi for always taking the time to assist me with the statistical analysis of this research. He has shown great support and patience as I sorted through my data. A big thank you also goes out to Katie Woods for her assistance with initial documentation and identification of skeletal elements at the Holliston Outdoor Research Facility. She helped me get this project started. Thank you all for your endless efforts!

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CHRISTINE A. JUNOD

Boston University School of Medicine, 2013

Major Professor: James T. Pokines, Ph.D., Professor of Anatomy and Neurobiology

ABSTRACT

Determining the postmortem interval in forensic cases becomes problematic at advanced stages when the decomposition of soft tissue ceases (generally less than six months) and radiocarbon dating cannot be applied (prior to AD 1950). Further research into bone weathering rates and patterns can aid in filling this large postmortem interval gap. Similar to soft tissue decomposition studies, the rate at which osseous weathering occurs needs to be studied regionally due to the significant effects of temperature fluctuations, sun exposure, and precipitation. This study investigates bone weathering rates and other taphonomic changes in New England. Other taphonomic changes that were investigated include carnivore scavenging patterns and tooth marks, rodent gnawing, and sources of color staining. The first part of this research was carried out in the White Mountain National Forest, NH on a sample of whole-carcass moose (*Alces alces*) deposited throughout the year due to vehicle collisions. Observations were made monthly and took place from December 2011 through October 2012. The second part of this research was conducted at the Boston University Outdoor Research Facility (ORF) in Holliston, MA on a sample of white-tailed deer (*Odocoileus virginianus*) long bones that were placed in three different microhabitats (grassland, wetland margin, and forest).

Field observations took place from February 2012 through February 2013. The hypotheses being tested were that the rate of weathering is dependent on seasonality and that it will vary among different regions and between various microhabitats. In both the White Mountain National Forest, NH and Holliston ORF, weathering stage 1 was first observed five months after deposition. Advancement in weathering was greatest during the Fall and Spring months when temperature fluctuations above and below freezing occurred most frequently. At this time, the results from Holliston ORF indicate that microhabitat is not a statistically significant factor of osseous weathering when examined 50 weeks after deposition ($p=0.53$). However, longer term data collection is needed in order to gather more meaningful information. Due to the short nature of this study in relation to weathering, this research will serve as a preliminary investigation and is intended to be carried out through the coming years.

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LIST OF ABBREVIATIONS

amsl	Above mean sea level
cm bgs	Centimeters below ground surface
NHFG	New Hampshire Fish and Game
ORF	Outdoor Research Facility
PMI	Postmortem interval
WMNF	White Mountain National Forest
WS	Weathering Stage

CHAPTER 1: INTRODUCTION

Assessing the postmortem interval (PMI) is largely a role of the forensic anthropologist and is one of the first questions sought after by investigators at a crime scene. Determining the PMI plays a major part in crime scene reconstruction and resolving forensic cases and legal matters. It answers such questions as when the individual died, where the individual died, what happened, and who the individual was (Wilson-Taylor 2012). Therefore, establishing a timeline of events is of great importance to forensic investigators (Swift 2006). However, estimating PMI is not precise and must be understood in the context of which the remains were deposited. Individual factors (body size and health/bacterial infection), environmental factors (climate and microenvironment), and cause of death greatly influence taphonomic processes (Behrensmeyer 1978; Galloway *et al.* 1989; Haglund *et al.* 1989; Haynes 1980; Kelly *et al.* 2009; Komar 1998; Mann *et al.* 1990; Megyesi *et al.* 2005; Miller 2009; Tappen 1994). This requires an understanding of the factors that influence postmortem changes and rates through the continued research of regional taphonomy.

The term taphonomy was first defined by Efremov (1940) as the study of the transition of organic remains from the biosphere into the lithosphere as the result of interrelated geological and biological phenomena. Research in this field initially developed as a branch of paleontology and later became recognized by anthropologists as an important concept to forensic analysis and the accurate interpretation of modifications of organic materials (Ubelaker 1997). Taphonomy has emerged as a critical component

of forensic anthropology, examining all the physical, chemical, and biological changes that may occur from time of death to locating the remains. Such processes include decomposition, osseous weathering, carnivore scavenging, rodent gnawing, trampling, bone transport, color staining, and thermal alteration. Increasingly, taphonomic research plays a crucial role in the advancement of forensic anthropology. Analysis and understanding of these processes can aid in determining the PMI and the reconstruction of events that may have occurred perimortem and postmortem. Furthermore, the environment into which human or animal remains are deposited will significantly influence the rate and pattern of the taphonomic processes that take place. Therefore, it is critical to conduct taphonomic studies across various regions of different climates in order to apply accurately PMI analysis and be able to distinguish between different types of taphonomic modifications.

PMI can be estimated based the observation of postmortem changes in relation to the external environment, and through corroboration of witness statements and/or other evidence. Several methods practiced today to aid in assessing PMI include soft tissue decomposition, entomology, plant root growth, associated artifacts, and radiocarbon dating of bone (Figure 1.1). The use of these methods mostly can be broken down into the early and late PMI, but are limited in their applicability. Generally, the longer the time since death, the more difficult it is to assess PMI. Hence, more research is needed to accurately assess the PMI, especially in the later interval. Understanding the rate of osseous weathering as it relates to time and environmental conditions can fill the PMI gap between where soft tissue decomposition ceases (generally less than one year or

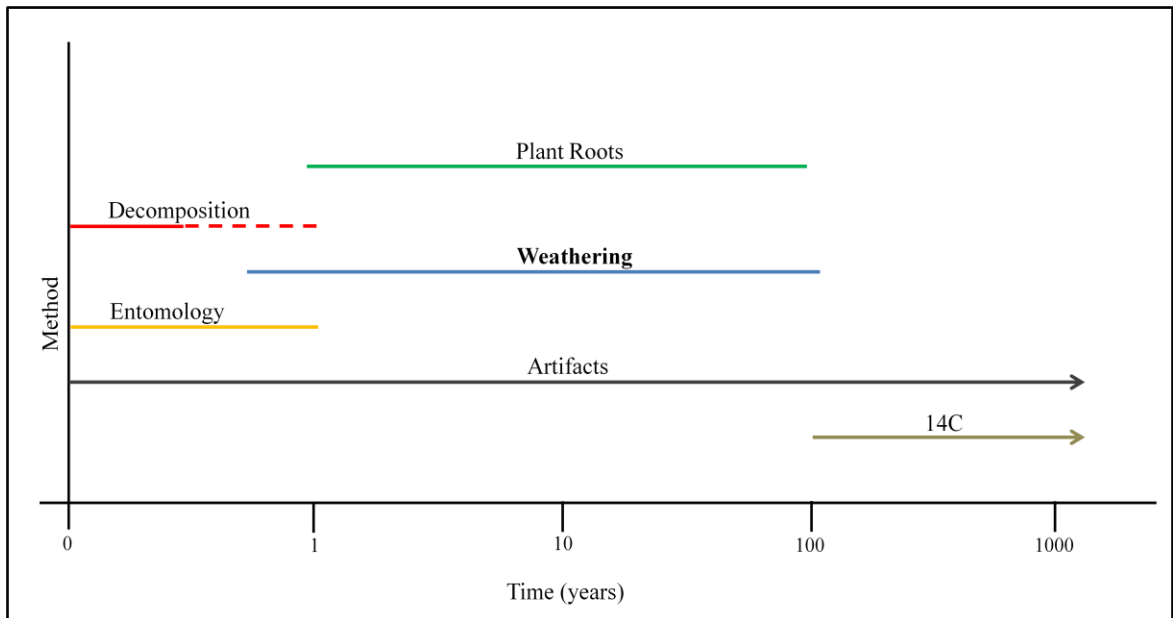


Figure 1.1. Common methods utilized to assess the postmortem interval.

much shorter) and the time at which radiocarbon dating of bone (prior to AD 1950) can be applied. The analysis of new plant growth based on annual growth rings and the dating of associated artifacts also may be used to fill the middle PMI range. However, forensic botany can rarely be applied and artifacts only provide circumstantial evidence. The research presented in this paper addresses the lack of viable options used to assess PMI following advanced stages of decomposition by further investigating the rate and patterns of bone weathering.

Methods commonly utilized to determine the time since death of recently deceased individuals includes the cooling (*algor mortis*) and stiffening (*rigor mortis*) of the body, decomposition stage, and entomological studies (Adlam and Simmons 2007; Bass 1997; Catts and Goff 1992; Cross and Simmons 2010; Davis and Goff 2000; Galloway *et al.* 1989; Haskell *et al.* 1997; Kelly *et al.* 2009; Komar 1998; Mann *et al.*

1990; Megyesi *et al.* 2005; Micozzi 1986; Pinheiro 2006; Pope 2010; Rodriguez and Bass 1985; Schotsmans *et al.* 2011; Simmons *et al.* 2010; Vass 2001; Wells and Lamotte 2010). Decomposition of organisms begins shortly after death through processes of autolysis (the breakdown of tissues by internal chemicals and enzymes) and putrefaction (the breakdown of tissues by microorganisms, especially bacteria). Generally, decomposition proceeds in sequential phases, such as fresh (*algor mortis* and *rigor mortis*), discoloration, bloating, active decay, advanced decay, and skeletonization, which broadly follow a timeline based on environmental factors and can be used to estimate PMI. However, decomposition is highly variable due to influencing factors such as temperature, humidity, clothing, burial type, scavenging, and body mass (Davis and Goff 2000; Galloway *et al.* 1989; Kelly *et al.* 2009; Ubelaker 1997; Wilson-Taylor 2012) and is only applicable prior to the onset of skeletonization (generally less than 6 months).

The use of forensic entomological studies also may be used to estimate time since death during the early stages of the PMI as insects are commonly the first organism to arrive at a decomposing body (in temperatures above 6°C) (Catts and Goff 1992; Haskell *et al.* 1997). Blowflies (*Calliphoridae*) oviposit on carrion almost immediately following death, thereby initiating a biological clock. The growth stage of the developing fly progeny can then be determined to assess the PMI. Furthermore, beetles (coleoptera) generally feed on the eggs and larvae of flies; therefore, determining the ratios in the succession of flies to beetles can be applied to the PMI (Byers 2008; Haskell *et al.* 1997). However, there are problems associated with this method. For example, weather and seasonality will influence the presence and developmental rate of insects, fly behavior

can vary between regions, and the timing of insect activity can be inconsistent (arrival, leaving the body, and reoccurrence) (Byers 2008; Wells and Lamotte 2010).

Furthermore, both of these methods (decomposition stage and forensic entomology) become difficult to apply at advanced stages of decomposition, resulting in the need to employ other methods for longer time intervals (Wilson-Taylor 2012).

The analysis of artifacts associated with remains at a crime scene, or a site suspected of being a crime scene, can provide information on the timing of burial or deposition. Human remains may be accompanied by a range of materials such as textiles (clothing or material used to wrap a body in), metal (weapons, tools, or fasteners on clothing), and paper products (including money) (Byers 2008; Janaway 2008; Morse 1983; Rowe 1997). Based on environmental conditions, these items are known to deteriorate at certain rates, some of which are better understood than others. Cotton is the most widely used textile and is also the least resistant to aggressive depositional environments, as it may break down in a matter of months. Synthetic fibers, such as nylon, acrylic, polyester, and elastin are less vulnerable to deterioration and may differentially survive decades (Janaway 2008; Rowe 1997). The corrosion of metal items is largely a factor of pH and redox. High redox values and acidic conditions result in increased rates of corrosion (Janaway 2008); thus, the active decomposition of remains will inhibit corrosion. The deterioration of paper products is also significantly influenced by the surrounding environment and is likely to be lost in a matter of months (Morse *et al.* 1983). The dating of artifacts can be used to distinguish recent burials from those of archaeological significance, at which time it becomes of interest to the state

archaeologist. In forensic cases, artifacts can usually only provide circumstantial evidence. Although the analysis of associated artifacts may provide a broad time interval between deposition and recovery, items may be quickly lost or may never have been dumped with the remains initially.

Far fewer methods exist which can be used to assess the late PMI. These methods are more rarely applied and include the study of botanical growth rates, such as the dating of annual rings of trees in direct association with the remains, radiocarbon dating of bone, and rates of osseous weathering. The use of forensic botany to estimate PMI relies on the recognition of flora associated with the remains and determination of growth rate for each species (Wilson-Taylor 2012). Analysis of new plant growth based on annual growth rings of roots that have grown through the remains or personal effects may be used to determine the minimum number of growing seasons since death (Walsh-Haney *et al.* 2010; Willey and Heilman 1987). This approach, however, only indicates a minimum time since death as the stems or roots may have not penetrated the remains the first season they were present. Other problems associated with this method are the distinction between annual growth rings and the rare applicability of it. Incomplete and false rings may be present due to wet and dry cycles within a year and unusual growing conditions. This approach also draws on the assumption of a standard rate of root growth, which is unlikely even for plants of the same species (Willey and Heilman 1978). Additionally, in cases where bone is known to have survived for a longer interval, radiocarbon dating can be used to estimate a time since death (Miller 2009; Swift 2006; Ubelaker *et al.* 2006; Wild *et al.* 2000). Recent studies have focused upon the modern bomb-curve to provide

age information in order to separate forensic from non-forensic cases (Ubelaker *et al.* 2006; Swift 2006). This approach, however, may provide age ranges that are too broad and overlap from historical to modern time periods.

Following skeletonization, the rate at which bone weathering proceeds may indicate the PMI when considering the context in which the remains were deposited. Weathering was defined by Behrensmeyer as “the process by which the original microscopic organic and inorganic components of bone are separated from each other and destroyed by physical and chemical agents operating on the bone *in situ*, either on the surface or within the soil zone” (1978:153). The role of environmental factors on the rate of bone weathering has received less attention and has been observed in far fewer contexts (Andrews and Cook 1985; Janjua and Rogers 2008; Miller 2009; Pokines 2009; Ross and Cunningham 2011; Tappen 1994). Further research into the processes and mechanisms of bone weathering would improve PMI determination and assist with forensic cases involving advanced stages of decomposition/skeletonization. In addition, if skeletal remains are moved from their original location or become buried, weathering patterns can help determine the original context of the bones. For example, previous studies have shown that the upper exposed surface of the bone typically weathers faster than the surface in contact with the ground (Behrensmeyer 1978; Miller 2009). Similarly, if bone becomes buried, weathering will become significantly delayed. The ability to recognize these patterns and understand the environmental influences plays an important role in resolving forensic cases.

In order to apply bone weathering stages to PMI estimates, weathering rates and patterns across regions need to be investigated to account for variations in different climates and within various microhabitats. Previous research has revealed that rates and patterns of bone weathering differ with changes in climate and are highly dependent on the microenvironment (Behrensmeyer 1978; Conard *et al.* 2008; Fiorillo 1989; Janjua and Rogers 2008; Pokines 2009; Pokines *et al.* 2011; Potmesil 2005; Tappen 1994; Ubelaker and Sperber 1988). This variation demonstrates the need for further investigation of bone weathering across different regions.

The purpose of this study is to further investigate the rate and patterns of osseous weathering in a temperate climate and determine the effects of microhabitat and seasonality. Weathering observations and changes were documented using an assemblage of moose (*Alces alces*) remains deposited in the White Mountain National Forest (WMNF), NH and a sample of white-tailed deer (*Odocoileus virginianus*) remains deposited in Holliston, MA. In the WMNF, data were collected throughout a ten-month period beginning in December 2011. Multiple times throughout the year, Conservation Officers from the New Hampshire Fish and Game Department (NHFG) use this area to deposit the remains of fresh road-killed animals, primarily moose and white-tailed deer. Conservation officers agreed to notify the author of freshly dumped animal remains. Conservation officers have been using this area to dump road-killed animals for at least fifteen years, but the exact duration of use is unknown. Permission to conduct taphonomic research at this location was obtained in writing by the author from the White Mountain National Forest Headquarters.

White-tailed deer remains were also deposited in Holliston, MA in three different microhabitats (grassland, wetland margin, and forest) to assess the influence of the immediate environment, such as protection from direct sunlight and the effects of moisture. The remains were placed in each microhabitat in February 2012, and data collection proceeded through February 2013. The data from Holliston and the WMNF were then compared with previous research to examine variations among different climates.

The hypothesis being tested is that the rate of weathering will vary among different regions and further is dependent on seasonality and microhabitat. Factors that will affect taphonomic changes include temperature, freeze/thaw cycles, precipitation, sun exposure, and vegetation growth (Andrews and Cook 1985; Beary 2005; Behrensmeyer 1978; Junod and Pokines in press; Miller 2009; Pokines 2009; Potmesil 2005; Tappen 1994). Skeletal remains that are directly exposed to UV radiation should begin to weather at a faster rate than remains deposited in locations that provide protection from sun exposure (Behrensmeyer 1978; Fiorillo 1989; Potmesil 2005). The rate of weathering is also expected to increase during the Fall and Spring when temperature fluctuations occur most often, resulting in reoccurring freeze/thaw cycles. Freezing of water within the crack and internal spaces of bone has the potential to cause significant damage. As water exerts pressure from expansion during freezing, the cracks and internal spaces of bone become greater; therefore, allowing the water to penetrate deeper during subsequent thawing. Reoccurring cycles may be a primary destructive factor advancing weathering in temperate climates where temperatures commonly

fluctuate above and below freezing during the Spring and Summer months (Junod and Pokines in press).

Additionally, other subaerial taphonomic changes that were analyzed throughout this study include carnivore scavenging and tooth marks, rodent gnawing, color staining, and insect activity. Freshly dumped moose in the WMNF provided the opportunity to observe whole-carcass scavenger consumption and patterns in the northeastern United States. This study sets out to investigate how these taphonomic processes (bone weathering, carnivore and rodent activity, and color staining) vary between and within different regions, and how they can be applied to determining the PMI and assist in resolving forensic cases.

CHAPTER 2: PREVIOUS RESEARCH

Bone Structure

In order to understand the process of bone weathering, it is essential to understand the components of bone structure. Bone is living tissue made up primarily of Type I collagen and a hydroxyapatite crystalline matrix. Collagen is a protein that provides bone with a soft framework to absorb tensile stress, while hydroxyapatite is an inorganic mineral that provides strength and hardens the framework (Loreille *et al.* 2007). When the collagen component becomes degraded, the bone becomes less capable of withstanding taphonomic processes and is more vulnerable to cracking.

On the gross level, bone is made up of dense, compact cortical bone and spongy, trabecular bone. Cortical bone forms the diaphysis in long bones and is found on the external surface covering trabecular bone. Trabecular bone is the internal porous bone found under protuberances, in irregular bones, epiphyses of long bones, and flat bones. Microscopically, immature bone forms rapidly and is made up of woven bone, which has a higher proportion of osteocytes than mature bone. Mature bone exhibits a lamellar structure which slowly replaces immature bone and is characterized by secondary osteons or Haversian systems. Secondary osteons replace primary osteons and can be densely packed or scattered in an unorganized fashion (Mulhern and Ubelaker 2001).

Dense haversian bone tissue is characteristic of the basic structural pattern in human bone, but haversian bone tissue may also be found in nonhuman bone (Hillier and Bell 2007; Martiniakova *et al.* 2006). Plexiform bone, characterized by its organized, horizontal, rectangular formation, is mostly characteristic of the cortical bone of large

animals, although it can rarely be found in human fetal bones and as primary osteonal formation in response to injury (Hillier and Bell 2007). Plexiform bone is laid down rapidly, creating radial bands that are not regularly seen in human lamellar bone (Mulhern and Ubelaker 2001). Based on these microscopic differences, the use of nonhuman skeletal remains in forensic research may not be directly applicable to human remains. However, the stress factors acting on the remains are the same and the weathering processes should follow similar patterns. The use of nonhuman skeletal remains in research is more easily attainable and therefore provides a larger sample size. Further comparative research is needed to shed light on these discrepancies.

Process and Patterns of Bone Weathering

Bone weathering is characterized by the cracking and flaking of the cortical surface, followed by the eventual loss of structure resulting from the loss of organic material, loss of moisture, and surface bleaching from UV radiation (Beary 2005; Behrensmeyer 1978). The rate at which collagen is lost is influenced by time, temperature, and environmental pH. High temperatures and extremes of pH will accelerate the loss of collagen, leading to the deterioration of bone (Collins *et al.* 2002). Contrary to living bone, dead bone has lost the ability to repair itself. As dead bone is continually subjected to environmental stresses, cracking and flaking become more prevalent. Weathering cracks proceed along the orientation of the osteons and follows the *split-line orientation* in bone (Tappen 1969, 1976; Tappen and Peske 1970). The split-line technique is carried out by producing punctures in wet demineralized bone by a

needle placed perpendicular to the surface, creating fissures (split-lines) that correspond closely to the orientation of the osteons. This process yields information about the functional structure of bone (Tappen and Peske 1970). In long bones, cracking can be observed following the long axes of the bone, while in irregular bones, cracking proceeds in multiple directions. The slow breakdown of bone due to weathering may only appear on the surface of the bone, while the interior cortical structure remains undamaged and intact (Fernández-Jalvo and Andrews 2003; Junod and Pokines, in press).

Miller (1975) and Behrensmeyer (1978) first introduced stage systems of bone weathering as it applies to large mammals (above 5 kg). Six weathering stages (WS 0 through WS 5) were described by Behrensmeyer (1978) based on the progressive pattern of linear cracking and flaking of the cortical surface, followed by formation of a rough fibrous texture, and eventual loss of bone structure (Table 2.1). When determining which weathering stage should be assigned, Behrensmeyer (1978) indicated that the most advanced stage covering an area larger than 1 cm² should be recorded, avoiding areas of physical damage, and all observers must agree concerning the stage. This progressive pattern of cracking and flaking is the basis for determining weathering stages and is broadly indicative of the period of surface exposure. While the rate of weathering is highly dependent upon climate and microhabitat, the stages of weathering seem to follow the same pathway as the pattern described above, regardless of environmental conditions (Buikstra and Ubelaker 1994; Madgwick and Mulville 2011; Miller 2009; Tappen 1994).

Table 2.1: Bone weathering stages as defined by Behrensmeyer (1978).

Stage	Description
0	Bone surface shows no sign of cracking or flaking due to weathering. Usually bone is still greasy, marrow cavities contain tissue, skin and muscle/ligament may cover part or all of the bone surface.
1	Bone shows cracking, normally parallel to the fiber structure (e.g., longitudinal in long bones). Articular surfaces may show mosaic cracking of covering tissue as well as in the bone itself. Fat, skin, and other tissue may or may not be present.
2	Outermost concentric thin layers of bone show flaking, usually associated with cracks, in that the bone edges along the cracks tend to separate and flake first. Long thin flakes, with one or more sides still attached to the bone, are common in the initial part of stage 2. Deeper and more extensive flaking follows, until most of the outermost bone is gone. Crack edges are usually angular in cross section. Remnants of ligaments, cartilage, and skin may be present.
3	Bone surface is characterized by patches of rough, homogeneously weathered compact bone, resulting in a fibrous texture. In these patches, all the external, concentrically layered bone has been removed. Gradually the patches extend to cover the entire bone surface. Weathering does not penetrate deeper than 1.0-1.5 mm at this stage, and bone fibers are still firmly attached to each other. Crack edges usually are rounded in cross-section. Tissue rarely present at this stage.
4	The bone surface is coarsely fibrous and rough in texture; large and small splinters occur and may be loose enough to fall away from the bone when it is moved. Weathering penetrates into inner cavities. Cracks are open and have splintered or rounded edges.
5	Bone is falling apart in situ, with large splinters lying around what remains of the whole, which is fragile and easily broken by moving. Original bone shape may be difficult to determine. Cancellous bone usually exposed, when present, and may outlast all traces of the former more compact, outer parts of the bone.

Effects of Macrohabitat on Bone Weathering

The rate of weathering varies across regions, based on broad differences in temperature regimes, precipitation, and vegetation, and these parameters are major factors when estimating PMI from weathering stage (Ubelaker 1997). Previous research has demonstrated that skeletal remains deposited in cooler, temperate climates can experience a longer duration of survival (Andrews and Armour-Chelu 1998; Andrews and Cook 1985; Fiorillo 1995; Miller 2009) than skeletal remains deposited in a semi-arid savanna climate (Behrensmeyer 1978; Coe 1978; Isaac 1967; Tappen 1994).

Furthermore, rainforest environments are known to slow the rate of weathering and extend the period of bone survival due to constant moisture, lack of freeze/thaw cycles, and dense protective vegetation (Kerbis Peterhans *et al.* 1993; Pokines 2009; Tappen 1994, 1995). These patterns generally indicate that the rate of weathering is slower in colder environments and locations where bones are protected from direct sunlight, and that warmer climates with a high UV index and/or high daily fluctuating temperatures tends to accelerate the rate of weathering. However, these patterns based on environmental factors remain variable as other previous research has indicated contradictory results (Andrews and Whybrow 2005).

Behrensmeyer (1978) examined large-mammal bone assemblages across six different habitats, including swamp, dense woodland, open woodland, plains, bush, and lakebed in the Amboseli Basin, southern Kenya. Weathering rates in Amboseli were analyzed using 35 carcasses with known dates of death. Behrensmeyer (1978) found skeletal elements reached WS 1 or 2 within a year and WS 5 within fifteen years of death. Large, longitudinal cracks often appeared on long bones only a few days after exposure. Although variation in the rate of weathering across microhabitats was noted, most bones that fell into WS 0, WS 1, or WS 2 had been exposed for three years or less. The author found that weathering was generally slower in areas that bones were kept moist and protected by swamp vegetation. Additionally, buried bones typically showed no signs of weathering, even if exposed sections of the bone revealed WS 4 or WS 5. Differential weathering on single bones was also observed between the upper (exposed) side of the bone and lower (ground contact) side, with the exposed surface often revealing more

advanced weathering. However, in some instances bones appeared more weathered on the lower surface of bones due to contact with highly alkaline soils where crystallization of salts caused flaking and splitting. Overall, the primary cause of increased weathering rates in Amboseli are likely due to extreme temperature and moisture fluctuations.

In another study in southern Kenya, Coe (1978) observed African elephant (*Loxodonta africana*) remains in the semi-arid grassland of Tsavo (East) National Park. Thirty percent of the elephant population had previously died due to a two-year severe drought, presenting an opportunity for taphonomic study. Two subadult and one adult African elephant sets of remains with known deposition dates were located and visited regularly over a four-year period. Although some of the remains (less than 15%) had been removed by spotted hyena (*Crocuta crocuta*) scavenging, most of the skeletal elements remained on or close to the death site. Coe noted that most skeletal remains showed flaking of the outer surface (WS 2) within four years of exposure and estimated that bone survival intervals are at least 20 years in this environment. Additionally, Isaac (1967) observed taphonomic changes of juvenile goats (*Capra hircus*) and cows in southern Kenya. Isaac (1967) noted that advanced stages of weathering (approximately WS 4 based on the descriptions) occurred after only seven years.

Similarly, Tappen (1992, 1994) found that bone weathering in the savanna environment at Parc National des Virunga (PNV), Zaire, is comparable to the morphological changes and rates noted by Behrensmeyer (1978). The longest duration of study was four years for a cape buffalo (*Syncerus caffer*) skeleton found recently dead. At two years after death, the bones had reached WS 1, with a few bones approaching

WS 2, and after four years of death, all of the bones had reached WS 2. The rate of weathering in the PNV is within the range of Amboseli, but on the slower end of the distribution, which may be attributed to the higher amount of rainfall (930 mm annually) and more equable climate. However, a longer duration of study is needed to ascertain further comparative data.

Skeletal remains that are deposited in open grassland and receive minimal shade will progress through weathering stages at an accelerated rate. Fiorillo (1989), in an analysis of partial ungulate skeletons deposited in a open field in Nebraska, noted that the remains appeared to correspond to the same pattern and rate of weathering as observed by Behrensmeyer (1978) in southern Kenya. The sample consisted of 84 bones from adult cattle and juvenile pig (*Sus scrofa*) selected from domestic carcasses that died of natural causes with known deposition dates. All six weathering stages were represented by this sample, with WS 1 occurring after one to three years and WS 5 observed after seven to eight years postmortem. Similarly, Potmesil (2005) studied taphonomic changes to cattle bone in an open grassland in Nebraska and noted that the bones deteriorated at a relatively constant rate, with each site representing a different weathering stage. The bones were exposed for approximately thirteen years, five years, and three years, and reached a maximum of WS 4, WS 2, and WS 1, respectively.

Conversely, rainforest environments can significantly delay weathering. Tappen (1994) investigated weathering rates of eight African elephant skeletons in the Ituri Rain Forest, Zaire. The PMI was known for only some of the remains, but the unknown deposition dates were believed to have been at least several years prior to observation

based on communications with local informants and the lack of bone grease and adhering soft tissue. Tappen determined that bone weathering was significantly delayed and sometimes absent in the Ituri Rain Forest. WS 0 was observed up to 16 years after death at one site, and the most advanced weathering stage (WS 3) was seen at least 15 years after death at another site. This can be attributed to the preservation of moisture content and protection from solar radiation due to dense vegetation.

Kerbis Peterhans *et al.* (1993) also suggested that much less subaerial weathering occurs in rainforest environments than in savanna contexts based on observations made in Kibale Forest, Uganda. All chimpanzee (*Pan troglodytes*) skeletal elements that were located were reported to be in WS 0. The minimal degradation that was noted on this sample was attributed to mammalian carnivore/scavenger activity. Weathering in general appears to be slower where bones are kept moist in climates that do not present seasonal freezing and are protected by vegetation and other forms of coverage (Behrensmeier 1978; Miller 2009; Pokines 2009; Tappen 1994).

In a more arid, colder, continental climate, Miller (2009) surveyed the large-mammal (ungulate) death assemblages of Yellowstone National Park (USA) to examine the fidelity of bone accumulations in relation to current and past populations.

Additionally, bone weathering characteristics were investigated across four different habitats (grasslands, forests, river-margins, and lake margins) using carcasses with known PMIs, as well as accelerator mass spectrometry (AMS) radiocarbon dating on some samples. Bone surveys yielded data on more than 10,000 bones and teeth from 24 species. Weathering stage distributions among the four habitats showed minor

differences that reflect variations in burial rates and changes in historical use among ungulate populations. Weathering characteristics were directly comparable to those noted in the savanna environment of Amboseli Park, Kenya (Behrensmeyer 1978). The initial stages of bone weathering rates were highly similar between the two locations, although bone survival while weathering was found to be significantly extended in Yellowstone. Bones may persist in each weathering stage for many years, with the exception of WS 0, in which case PMI was no greater than one year in either location. Individual surface-exposed elements could survive to a recognizable state (WS 4) for over 200 years as determined by ^{14}C dating in Yellowstone. Snow covering the bones for at least half of each year in Yellowstone is likely a dominant factor in the long-term preservation of bone, as it limits microbial activity, fluctuations in temperature and humidity, and UV radiation.

Similarly, in central Wales, Andrews and Armour-Chelu (1998) studied a surface assemblage from natural deaths of sheep (*Ovis aries*). The sample size consisted of 133 bones in which humeri and scapulae were the best-represented elements whereas radii, mandibles, and metapodials were poorly represented. The authors found that the majority of skeletal elements (62.5%) showed no signs of weathering, and none of the bones had reached the most advanced stage of weathering (WS 5). The overall time of exposure was unknown, but continuous observations indicated that weathering rates tend to be much slower when compared to equatorial Africa (Behrensmeyer 1978) and that few bones displayed weathering beyond WS 2 after 22 years of exposure. The authors suggested that other taphonomic agents may destroy bone before advanced stages of

weathering are reached. These agents include corrosion due to acidic soils and the loss of bone as a result of carnivore gnawing.

Fiorillo (1995) also noted a prolonged survival rate of skeletal remains studied in a subalpine, open grassland climate of southwest Colorado. Complete and partial skeletons, isolated bones, and bone fragments were observed, consisting of 214 mammal specimens (ungulates, rodents, and lagomorphs) and 14 bird specimens (small passerines). While all weathering stages were represented in this sample, WS 0 revealed the highest frequency (41%) followed by WS 1 (25%), WS 2 (12%), WS 3 (10%), WS 4 (10%), and WS 5 (2%). The time of exposure was unknown; however, Fiorillo (1995) suggested that the abundance of elements representing WS 0 is likely a result of the predominantly low temperatures.

Although comparable weathering rates have been observed between areas of similar climates, other studies reveal contradictory results (Andrews and Whybrow 2005). Andrews and Whybrow (2005) monitored a camel (*Camelus dromedarius*) skeleton for 15 years in an arid environment in Abu Dhabi, United Arab Emirates. Estimated exposure time was thought to be closer to 17 years, since the skeleton was disarticulated and the presence of soft tissue was minimal at the time of discovery. This arid environment lacks vegetation for shade, experiences large daily temperature fluctuations, and burial is expected to be slow due to periodic flash floods in wadi systems caused by heavy rainfall. Under these environmental conditions, the potential for bone survival was expected to be low, but weathering was noted to be substantially slower when compared to weathering rates in tropical environments. After eight years of

exposure, most bones had barely reached WS 1; after 10 years, most bones were between WS 1 and WS 2; and after 15 years, most bones had reached only WS 3. This pattern was observed for bones that were exposed on the surface for the entirety of the study. Bones that had become deeply buried showed little or no weathering after 15 years.

Effects of Microhabitat on Bone Weathering

Bone weathering occurs at different rates in various microhabitats based on vegetation cover, soil acidity, proximity to water, burial potential, and other elements that act to preserve or degrade bone. Slight variations within a microhabitat also influence weathering rates and is made apparent by the fact that a single bone can and usually does portray different stages of weathering (Behrensmeyer 1978; Miller 2009; Ubelaker and Sperber 1988). Tappen (1994) noted low rates of weathering for bones exposed on a rainforest floor but which were protected from direct sunlight exposure by thick vegetation. Common alterations noted on the remains in this environment included green algae growth on the exposed surfaces (79% of the bones), termite damage (59% of the bones), and rodent gnawing (56% of the bones). Similarly, in a tropical rainforest environment in Papua New Guinea, Pokines (2009) noted that no osseous weathering occurred after 58 years. The sample consisted of ten sets of human remains that were a result of a WWII bomber crash. Although the low rate of weathering can be attributed to the macroenvironment (rainforest), it is also a result of the protective nature of the aircraft wreckage and dense forest canopy (microenvironment). Most alterations present

on the remains were due to contact with the acidic topsoil and surface etching by plant roots.

In the UK, Andrews and Cook (1985) studied bone modifications of a single cattle (*Bos taurus*) carcass and noted that weathering was impeded, likely due to the immediate environment. The carcass rested on a shelf covered by limestone clasts after it fell from a cliff, which did not result in any bone fractures. The location was isolated from scavenger activity and human disturbance, although the area was used as a pathway for cattle herds. By six months PMI, the scapulae, pelvis, limbs and segments of the spine were disarticulated. The site was visited annually to document taphonomic modifications. The skeletal elements did not portray any signs of weathering after an eight-year period. These elements were largely protected by the local vegetation and terrain. The primary agent of dispersal and damage to the bones was due to the kicking and trampling by cows and the gravitational movement down an adjacent gully. No signs of gnawing were observed. Bone surface modifications (striations and scrapes) were superficial, closely spaced, intersecting, of variable curvature and breadth, and therefore could be attributed to root etching, gravitational movements, and trampling.

Caves also provide constant protection from direct sunlight exposure and contribute to bone preservation over a long period. Brain (1980) studied bovid bone accumulations in caves in various parts of Southern Africa. Most bones that were located in a porcupine (*Hystrix africaeaustralis*) lair displayed signs of weathering, indicating that the bones had weathered from surface exposure prior to being collected by porcupines. Porcupines show a preference for bleached, defatted bone (Brain 1980;

Pokines and Tersigni-Tarrant 2012; Roze 2009). Brain noted that unless bones are defatted before collection in a cave, the bones will continue to exude grease indefinitely due to the protection from sun exposure. Pokines *et al.* (2011) studied taphonomic changes of megafauna and microfauna remains located within a large, open sinkhole in a semi-arid environment near Wadi Zarqa Ma'in, the Dead Sea area, Jordan. Very few elements had undergone significant weathering despite their surface deposition. The rate of weathering was slowed due to the lack of direct sunlight and whole carcass deposition. The depositional environment of the remains also resulted in limited scavenging, slower decomposition rates, and mummification of the soft tissue.

Ubelaker and Sperber (1988) noted that weathering can be highly localized on a skeletal element where sun exposure only strikes that part of the element in an otherwise protected artificial environment. Human skeletal remains were discovered in an unused cistern in Nebraska. Bleached, circular spots were noted on the top of the cranium, a pattern inconsistent with the rest of the skeleton. The authors determined that these spots were a result of sunlight beaming through perforations in the manhole cover above. This is consistent with the general observation that most bones are more weathered on the top (exposed) surface than on the bottom surface. These studies illustrate how direct sun exposure can accelerate the rate of collagen loss, leading to a change in bone matrix organization and ultimately resulting in a mineral "ghost" (Collins *et al.* 2002).

Microenvironment also may affect how quickly skeletal remains become partially or completely buried after deposition, influencing the exposure time and ultimately hindering weathering processes (Andrews 1995; Behrensmeyer 1978, 1983; Miller 2009;

Ross and Cunningham 2011; Serjeantson 1991; Shipman 1981; Tappen and Peske 1970; Todisco and Monchot 2008). Well-preserved buried bones may indicate rapid burial, whereas highly weathered, buried bones imply a longer exposure length prior to burial (Todisco and Monchot 2008). The rate of burial of surface-deposited remains may vary due to a number of factors, such as decaying vegetation build up, erosion, and trampling. In turn, the burial environment will affect overall skeletal preservation based on soil pH and water fluctuations (Crow 2008; Gordon and Buikstra 1981). Hill (1980) noted that buffalo (*Syncerus caffer*) skeletal remains buried in a mud wallow in southwest Uganda were found in near-perfect condition 52 months since death. Similarly, Behrensmeyer (1978) noted that partially buried bones generally revealed no signs of weathering even when the exposed portion had reached WS 4 or 5. Conard *et al.* (2008) studied a faunal accumulation in the Geelbek Dunes of South Africa, which is continuously affected by cycles of open air exposure and burial. This cycle subjects the elements to daily heating and cooling and wetting and drying, leading to the more rapid destruction of cortical bone and the survival of more porous bone. Although the extent of weathering is related to the time of exposure, weathering progresses at different rates in various microenvironments, thus making it more difficult to determine a standard rate at which weathering stages advance (Shipman 1981:115).

Other Taphonomic Changes to Surface Remains

Other taphonomic changes to bone are commonly observed with weathering. Being able to recognize and distinguish among these changes is an essential aspect of

taphonomy that may aid in determining PMI and establishing the original context of the remains if moved from the initial location. Common taphonomic processes include carnivore and rodent gnawing, algae, lichens, and moss growth, and color staining. The environment in which deposition takes place will influence the pattern and rate in which these processes occur (Alden and Cassie 1998; Haefner *et al.* 2004; Haglund 1992, 1997; Haglund *et al.* 1989; Haynes 1980; Mattson 1997).

Carnivore Scavenging

The environment and season in which large vertebrate remains are deposited will influence the type and pattern of scavenging. The degree of utilization of any large carcass is influenced by the number of carnivores feeding, time of year, type of site, and hunger levels (Haynes 1980). Understanding scavenging patterns provides valuable information for forensic investigations as it can aid in determining the location of human remains and the ability to distinguish animal bone alterations from other taphonomic changes. Conducting scavenging studies throughout different regions can aid in understanding patterns of scavengers specific to the local area. Scavenging results in soft tissue modification and consumption, disarticulation, modifications to bone, and the scattering of remains (Haglund 1997). The consumption of soft tissue can accelerate the rate of decomposition, exposing the bones to other environmental elements and taphonomic processes. Disarticulation of human or animal remains by scavengers also makes the bones transportable and more difficult to recover.

Coyotes (*Canis latrans*) and dogs (*Canis familiaris*) are common canids responsible for scavenging in the Pacific Northwest, USA, and are known to act in a predictable pattern (Haglund 1997; Haglund *et al.* 1989). This pattern is divided up into five sequential stages (stage 0-4), starting with scavenging of soft tissue, and progressing to destruction of the ventral thorax associated with evisceration and disarticulation of one of both upper extremities, partial or full removal of the lower extremities, disarticulation of all remaining skeletal elements except for segments of the vertebral column, and total disarticulation. In an observational study conducted on 46 partially to fully skeletonized human remains recovered from the Pacific Northwest, Haglund *et al.* (1989) found that 30 of the 46 cases revealed carnivore scavenging, 22 of which corresponded to the defined stages. Half of the cases which revealed atypical scavenging patterns were located within sheltered circumstances that limited exposure to scavengers, and the other half were located within high human population areas. Similarly, the majority of the 16 cases that were not scavenged were also located in areas of high human population densities. Total disarticulation of all skeletal elements, except for segments of the vertebral column (stage 4), was initially seen as early as two months postmortem. However, scavenging may be initiated or abandoned at any time. The species of scavengers is also specific to the environment and may be influenced by seasonality and the stage of decomposition of the remains.

In an observational taphonomic study carried out in northeastern Minnesota, USA, Haynes (1980) recorded data on white-tailed deer remains that had been killed by wolves (*Canis lupus*). Kill site locations and information was provided by local wildlife

biologists. Haynes noted that most organs and blood are the first to be consumed, followed by the upper rear legs which, in the same process, exposes the proximal ends of the femora and the pelvic girdle, resulting in gnawing damage to the bones there. As soft tissue consumption proceeds, ribs, vertebrae, and scapulae are exposed and subjected to carnivore damage, while the consumption of the neck and head follows. Hind limbs and forelimbs become disarticulated, and the deer may be rolled and twisted into different positions. This pattern is most commonly observed when two or more wolves are feeding. In this case, disarticulated limbs may be removed from the kill site within a couple of hours. Single wolves tend to focus on one aspect of the carcass, subsequently carrying off disarticulated lower limbs or single bone elements up to 30 meters (100 feet) from the primary kill site. After the consumption of the carcass by wolves, foxes (*Vulpes vulpes*), ravens (*Corvus corax*), and fisher (*Martes pennanti*) were observed gnawing on the remnants. Survival of skeletal elements at the kill site can vary but still follows a general pattern. If consumption is low, the head and neck may not be damaged, although in other cases only fragments of the mandible may remain. The sternum is typically fully consumed, and multiple ribs may remain articulated to the vertebrae. The scapulae become disarticulated early and may show carnivore damage only along the vertebral border. The pelvis may remain articulated to the sacrum, or may become separated and destroyed by gnawing. Long bones are commonly broken. The olecranon process of the ulna, along with the epiphyses of other long bones, is typically gnawed off. Haynes (1980) states that damage to carcasses from kills will be more severe than damage from scavenging but will still share similar characteristics (Table 2.2).

Table 2.2. Comparison of carnivore scavenging and kill site patterns in the Pacific Northwest (Haglund *et al.* 1989) and Minnesota, USA (Haynes 1980).

Location	Sample	Scavenging Patterns/Stages	Other Observations
Pacific Northwest (Haglund <i>et al.</i> 1989)	46 human remain cases scavenged by coyotes and dogs	Removal of soft tissue; destruction of the ventral thorax and removal of upper extremities; removal of lower extremities; only segments of the vertebral column remain articulated; total disarticulation and scattering	Total disarticulation (except for the vertebral column) was observed after 2 months of death; maximum recovered distance of scattered remains was 180 meters
Minnesota, USA (Haynes 1980)	White-tailed deer remains killed by wolves	Removal of soft tissue; consumption of upper rear legs; consumption of the thorax followed by the neck and head; hind and forelimbs become disarticulated	Damage from kill sites is more severe than from scavenging; whole-carcasses were almost completely consumed in less than 2 days at kill sites; maximum recovered distance of scattered remains was 30 meters

Low densities of moose in parts of Alaska and Canada can be accounted for by predation of brown/grizzly bears (*Ursus arctos*), and in other areas, black bears (*Ursus americanus*) (Mattson 1997). In a study conducted in Yellowstone National Park, USA, Mattson (1997) analyzed predation and scavenging patterns of grizzly bears on ungulates. The author concluded that grizzly bears obtain much of their caloric intake from ungulates. The majority of ungulate meat consumed came from elk (*Cervus canadensis*), followed by bison (*Bison bison*), moose, domestic livestock, and mule deer (*Odocoileus hemionus*). Scavenging was most prevalent in the Spring, which was associated with the abundance and availability of carrion. Small-bodied ungulates seemed to be the preferred prey, while moose were selectively preyed on.

Saladié *et al.* (2013) examined patterns of bone modifications caused by modern brown bears. At the Barcelona Zoo, 206 sheep, pig, and cow bones were fed to three captive brown bears. The pig and sheep elements used were articulated and not defleshed, while the cattle bones were defleshed with some soft tissue remaining on the ends. The authors concluded that bears are typically agents of slight to moderate bone modification and show a preference for large-sized animal bones. However, intense modification was seen on small to medium sized bones and on juvenile remains, occasionally consuming whole epiphyses. While some soft tissue consumption occurred without any bone modification, the tooth marks that were observed revealed the same morphology as other large carnivores. In some cases, the force of the bite caused crushing across large areas of bone.

Common types of tooth marks, **pits**, **punctures**, **scores**, and **furrows**, have been recognized as common bite patterns produced by carnivores on bone and are defined in the taphonomic literature (Binford 1981; Lyman 1994; Pobiner 2007; Pokines and Tersigni-Tarrant 2012). Tooth pits and punctures are the result of pressure from the tooth on the bone surface and have a circular appearance with a bowl-shaped cross-section. Cortical bone flakes may be pressed into the tooth mark depression, causing the internal surface to appear crushed. Pits are small, shallow indentations that do not penetrate the cortical surface of the bone, while punctures are deeper indentations that do penetrate the cortical layer of bone. Tooth scores and furrows are linear marks of variable length and appear U-shaped in cross section. They are produced by a tooth dragging across the

surface of a bone. Scores do not penetrate the cortical layer of bone, while furrows are deeper marks that do penetrate the cortical layer of the bone.

Rodent Gnawing

Rodent gnaw marks are distinct from carnivore gnaw marks in that they produce long, parallel striations rather than circular pits and punctures. Their unique lower jaw is loosely joined at the symphyseal region, allowing for a greater range of motion in which the mandible can freely move forwards and backwards multiple times, creating the parallel striations (Haglund 1997). The purpose of rodent gnawing on bone is threefold based on herbivorous or omnivorous dietary reasons. Rodent gnawing is related to the necessary wearing down of incisors, as well as attaining nutritional needs from the fat containing trabecular bone or from the mineral component of the bone (Klippel and Synstelien 2007; Pokines and Tersigni-Tarrant 2012; Roze 2009). Rodents have paired open-rooted incisors that continue to grow throughout life and require regular attrition to keep them at a usable length (Brain 1980). Additionally, black rat (*Rattus rattus*) and brown rat (*Rattus norvegicus*) are omnivores and consume fresher remains in which fat is still present in the trabecular bone, while porcupine species tend to be attracted to the mineral content (Klippel and Synstelien 2007; Pokines and Tersigni-Tarrant 2012; Roze 2009). In a taphonomic study carried out at University of Tennessee's Anthropological Research Facility using human remains, Klippel and Synstelien (2007) noted that brown rats prefer marrow-enriched long bone ends and modify bone in a pattern consistent with obtaining soft tissue nutrients, primarily fat. Conversely, on a small island in Lake

Temagami, Ontario, Coventry (1940) noticed the daily occurrence of a red squirrel (*Sciurus hudsonicus*) gnawing on a dry, weathered moose skull. Various rodent taxa are commonly known to gnaw on dry bone, but it is undetermined if the primary reason is due to incisor-sharpening or consumption of the mineral content (Pokines and Tersigni-Tarrant 2012).

Haglund (1992) presents three case studies in which rodents utilized mummified soft tissue, fresh bone, and dry bone. In the first case, the recovery of a cranium with a PMI of twenty years revealed classic rodent gnaw marks (parallel striations) along the supraorbital margin and zygomatic arch. The second case involved a suicidal hanging that was discovered in a wooded area approximately seven months following the individual's death. Brown rats were discovered living within the thoracic cavity, along with a tunnel leading from the thoracic area to the posterior aspect of the left shoulder. Rodent gnaw marks were observed on skeletonized elements of the body, along with chewed edges of dried muscles and mummified skin. Lastly, an individual body was discovered in a wooden shack three days after death. Damage to soft tissue caused by rodents was observed across multiple areas of the body. The damage occurred in a layered fashion and exhibited finely serrated, scalloped edges. These cases demonstrate the scavenging of soft tissue and bones by rodents and the use of human remains for nesting purposes.

Algae, Lichens, and Moss

Algae, lichens, and moss growth are commonly seen on the surface of exposed bone. Algae growth is dependent on nutrients, moisture, and sunlight. Algae are a diverse group of simple organisms that can grow in salt water, fresh water, and on land in which they attach to a substrate such as sand, rock, a pier, or some other surface (Alden and Cassie 1998). Thus, algae also can develop on surface exposed bone or bone submerged in shallow water (Haefner *et al.* 2004). Lichens are made up of a fungus and symbiotic microscopic green algae or cyanobacteria that can occur in a broad range of habitats, including desert, alpine, and forest. They can survive in various temperatures and withstand harsh conditions. The growth rates of lichens are extremely slow, at approximately one quarter to one half of an inch per year (Alden and Cassie 1998). Due to their slow growth rate, archaeologists have previously used lichens as a dating method for archaeological sites (Benedict 2009). At the same time, large portions of surface coverage on bone are rarely observed as other destructive forces are acting on the bone. Mosses (*Bryophyta*) are feathery, mat-forming spore plants that are generally found in moist environments. Mosses lack a vascular system and must absorb water and nutrients directly from the environment (Alden and Cassie 1998). Therefore, the presence of moss on bone is indicative of a moist, terrestrial, sunlit environment.

Color Staining of Bone

Environmental conditions surrounding the deposition of remains can result in various degrees of color staining. Environmental factors leading to discoloration of bone

includes sun exposure (progressive bleaching), organic and mineral content of soil, contact with green algae or artificial alloys. Additionally, any remaining soft tissue on skeletonized remains can result in color staining of the bone. In forensic cases, examining different patterns of staining may provide information on bone deposition, if the bone has been moved from its original location, and could possibly aid in determining PMI.

In a study that investigates the events surrounding bone deposition based on color staining, Huculak and Rogers (2009) used 40 juvenile pig humeri with minimal tissue attached to create different scenarios of primary and secondary depositional environments. Half the bones were buried for four weeks then exposed on the surface for four weeks, while the other half were first exposed on the surface then buried. Huculak and Rogers (2009) observed five main color differences: light yellowish brown due to soil staining, dark reddish brown due to hemolysis, white due to sun bleaching, dark reddish gray from decompositional fluid staining, and greenish gray to olive due to the presence of fungi. Bleaching was more prevalent on the bones that were buried first then exposed on the surface, and these bones did not contain any fungal growth. In contrast, the bones that were exposed on the surface first then buried exhibited fungal growth but no bleaching. A cross-sectional analysis revealed that the bones that were buried then exposed exhibited a color pattern of light to dark from the outer to inner cortex, while the bones that were exposed then buried exhibit a color pattern of dark to light from the outer to inner cortex. Huculak and Rogers (2009) concluded that the presence of fungi may be

valuable for determining the sequence of events surrounding body deposition, and that a cross-sectional analysis of color can be used for verification.

Bleaching of the bone due to solar radiation is one of the earlier taphonomic changes that occurs, but it has been largely overlooked as a potential method for establishing PMI (Beary 2005). Beary (2005) examined the effects of UV radiation on color changes of bone and how this may be applied to the determination of PMI. A digital spectrophotometer was used to standardize and quantitatively track the color changes in bone resulting from bleaching. Using a sample of 60 white-tailed deer rib segments, 30 bones were exposed to natural sunlight, while the other half were observed in an indoor experimental setting where variables could be controlled. After one month of observations, Beary (2005) noted that the bones were altered in a predictable fashion and concluded that a significant relationship exists between the duration of UV exposure and the degree of color change due to surface bleaching. Furthermore, surface bleaching is initiated immediately with exposure to solar radiation. This research indicates that models can be developed for estimating solar radiation exposure durations based on progressive color changes. However, similar to other taphonomic changes, varying climatic factors will significantly influence the duration patterns and need to be considered when assessing PMI. Overall, additional taphonomic research needs to be conducted to assess regional variations and glean meaningful data that can be used to resolve forensic cases.

CHAPTER 3: METHODS

White Mountain National Forest, New Hampshire

Environmental Analysis

Taphonomic data were collected throughout the length of this study on a white-tailed deer and moose carcass dump site in the White Mountain National Forest near Twin Mountain, New Hampshire. Figure 3.1 shows the location of the dump site in relation to the second study carried out at the Holliston Outdoor Research Facility (ORF). The New England landscape has changed drastically over the past few hundred years. Historically, New England was substantially covered by forests, but throughout the 18th and 19th century the landscape was slowly cleared for agriculture, with New Hampshire being about one-half cleared. By the mid-20th century, agriculture declined dramatically, resulting in one of the most significant impacts on the New England forested landscape. It caused major changes in soils, loss of nutrients, and cover-type shifts from hardwoods to spruce-fir (Compton and Boone 2000; Foster *et al.* 2002; Gerhardt and Foster 2002). As habitat conditions changed over this period, changes in wildlife populations also occurred. Predators of livestock, such as wolves and mountain lions (*Puma concolor*) were hunted, and other species, such as the white-tailed deer, black bear, and wild turkey (*Meleagris gallopavo*) had retreated and disappeared from their former range (DeGraaf *et al.* 2006). With the return of the forest during the late 19th century, most of these populations returned or had been reintroduced into their former habitat. Forest re-growth is still occurring, and wildlife populations continue to increase and expand their ranges throughout the area. However, habitat diversity is declining as forests have matured



Figure 3.1. Location of WMNF carcass dump and Holliston ORF (yellow pins). Google Earth 2013.

(Foster *et al.* 1998, 2002). Currently, approximately 80% of Northern New England is covered by hardwood and conifer forests (DeGraaf *et al.* 2006).

The changing forests of New England can be classified into six regions (Spruce-Fir, Northern Hardwoods, Northern Hardwoods-Spruce, Transition Hardwoods-White Pine, Central Hardwoods-Hemlock-White Pine, and Pitch Pine Oak) based on physiography, climate, bedrock mineralogy, topography and soils. Northern Hardwoods and Spruce-Fir are the primary types found in northern New England (DeGraaf *et al.*

2006; Tang *et al.* 2012). The study site located in the WMNF falls within the Northern Hardwoods-Spruce Forest region, which occurs below 853 meters (2,800 feet) in central and northern New Hampshire and southern Vermont. The tree species that largely characterize this area include beech (*Fagus grandifolia*), white birch (*Betula pendula*), yellow birch (*Betula alleghaniensis*), sugar maple (*Acer saccharum*), and associated conifers. Hemlock (*Tsuga canadensis*) is present at lower elevations, and red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) occur at higher elevations. Spruce and fir occupy northerly exposures and mountaintops, while hemlock and white pine (*Pinus strobes*) characterize southerly exposures (Alden and Cassie 1998; Davis *et al.* 1980; DeGraaf *et al.* 2006; Goodale 2003; Tang *et al.* 2012).

Northern New England is characteristic of a humid, cold temperate climate, receiving an average of 1575 mm (62 in) of rain per year and a yearly average temperature of 5.5° Celsius (42° Fahrenheit). The Summers tend to be more mild, and the Winters are cold. The average date of the first frost is September 15, and the average date of the last frost is June 1, with an average of 90-120 frost-free days. Mean annual snowfall ranges from 2032-3048 mm (80-120 in) (DeGraaf *et al.* 2006; Tang *et al.* 2012).

Site Description

Permission to conduct taphonomic research at this location was obtained in writing by the author from the WMNF Headquarters. The carcass dump research area is located at N 44° 15' 02.1" W 71° 29' 40.1", approximately 15 kilometers west of Mount Washington, at an elevation of 550 m (1,800 ft) above mean sea level (amsl). The site is

located approximately 1.6 km down a gated forest service road, limiting the amount of human intrusion. However, hikers have been seen along the forest service road on multiple occasions. The site is unfenced, with approximate dimensions of 80 m east-west by 70 m north-south. It is located on a 5-15° west-facing slope in a mixed deciduous forest, with a seasonal drainage that runs west through the middle of the site. Known scavenging species and local vegetation information was obtained from New Hampshire Fish and Game (NHFG). Scavenging species include common raven (*Corvus corax*), red fox, coyote, raccoon (*Procyon lotor*), bobcat (*Lynx rufus*), and domesticated dog. During the warmer months, American black bears are known to scatter the remains. Local vegetation specific to the site includes white spruce (*Picea glauca*), rock maple (*Acer glabrum*), sugar maple, striped maple (*Acer pensylvanicum*), balsam fir, highbush blackberry (*Rubus argutus*), serviceberry (*Amelanchier arborea*), hobblebush (*Viburnum lantanoides*), speckled alder (*Alnus incana*), herbs, and forbs. Considering the deciduous environment of this site, the fluctuating temperatures, and snowfall, seasonality was expected to have a significant impact on the rate of weathering and will influence the microenvironment. Figures 3.2 and 3.3 depict an overview of the area and the vegetation differences in the late Fall (November) and Summer (June) with the sample exposed to direct solar radiation in the Fall, while shaded by dense vegetation during the Summer.

According to Conservation Officers with NHFG, vehicle collision carcasses have been continually dumped at this location for at least fifteen years. The maximum number of years this site has been in use could not be determined. The site consists of a large whole-carcass sample, containing mostly moose and white-tailed deer remains, although



Figure 3.2. WMNF carcass dump overview, facing West, November 2011.



Figure 3.3. WMNF carcass dump overview, facing West, June 2012.

other species such as black bear are occasionally dumped at this location as well. An average of twelve fresh road-killed carcasses are dumped at this location per year. The number of road-killed animals increases during the Spring, as there tends to be more animal movement near the road at this time due to snow melt first occurring in this area. During the Winter months, the animals tend to congregate to south-facing slopes located in mixed conifer forests away from the road. Conservation Officers agreed to notify the author when new remains were deposited.

Data Collection

In October of 2011, an initial block survey of the area was conducted on foot along transects two meters apart to locate and flag bones (Figure 3.4). The survey area covered a 100 meter radius. If an outlier was located, the search was extended another 30 meters past that point. Areas of bone concentrations were documented using a Garmin GPS unit and are accurate up to plus or minus a maximum of seven meters. Taphonomic data collection began in November 2011 and was carried out until October 2012. Observations occurred monthly with the exception of January 2012 through March 2012 due to snowfall making the area inaccessible. Field research continued in April 2012 at first sign of snowmelt.

Eighty-five isolated moose skeletal elements were initially identified and documented. Each skeletal element was labeled using aluminum numbered tags secured to the bone. Throughout the study 41 additional bones (mostly ribs and vertebrae) were added to the sample as three moose carcasses were deposited, for a total of 126 isolated

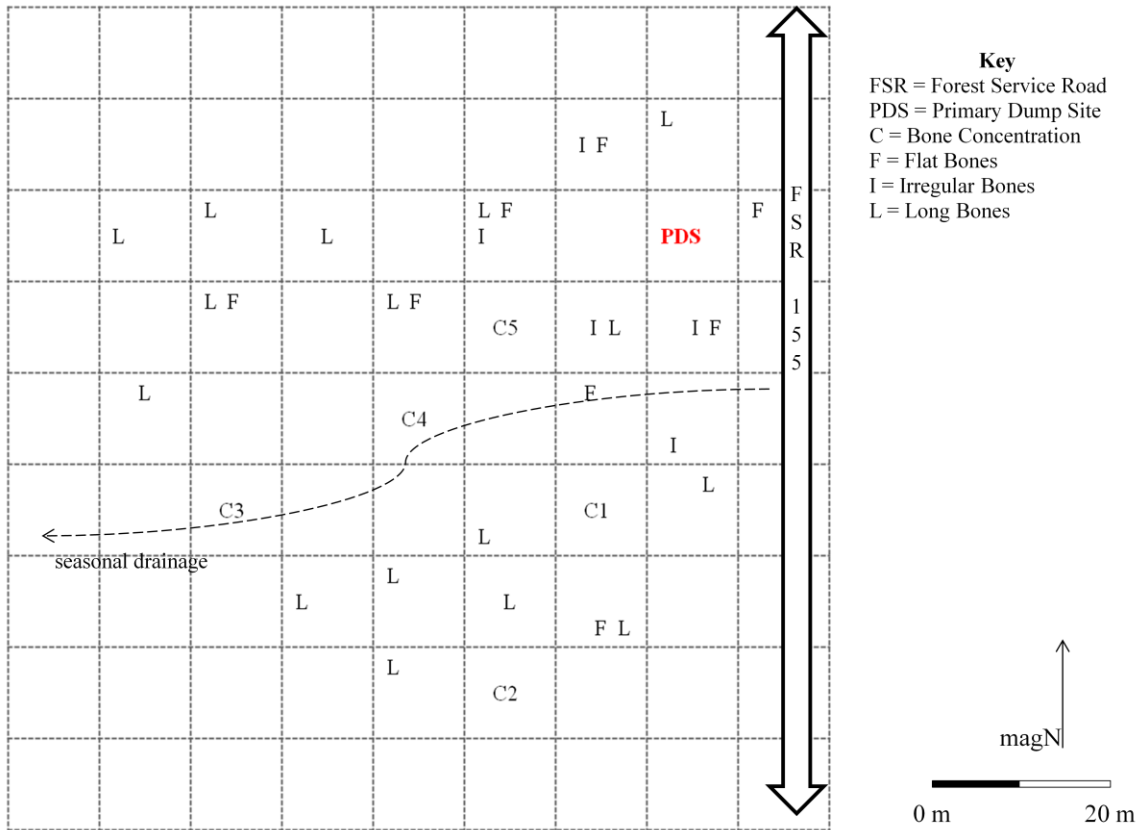


Figure 3.4. WMNF site, location of bone concentrations (C1-C5) and outliers in relation to the primary dump area adjacent to forest service road 155.

bones. The three moose carcasses also provided temporary peaks in bone samples that were quickly lost due to animal scavenging. Not all isolated skeletal elements could be relocated each visit due to animal scavenging, human intrusion, and dense vegetation growth. Approximately one-third of the skeletal elements could not be relocated in July due to thick vegetation covering the forest floor. However, with the use of a Garrett Ultra Investigator G-500 metal detector the following visit, 90% of the bones were relocated. The frequency of each type of skeletal element is represented in Figure 3.5.

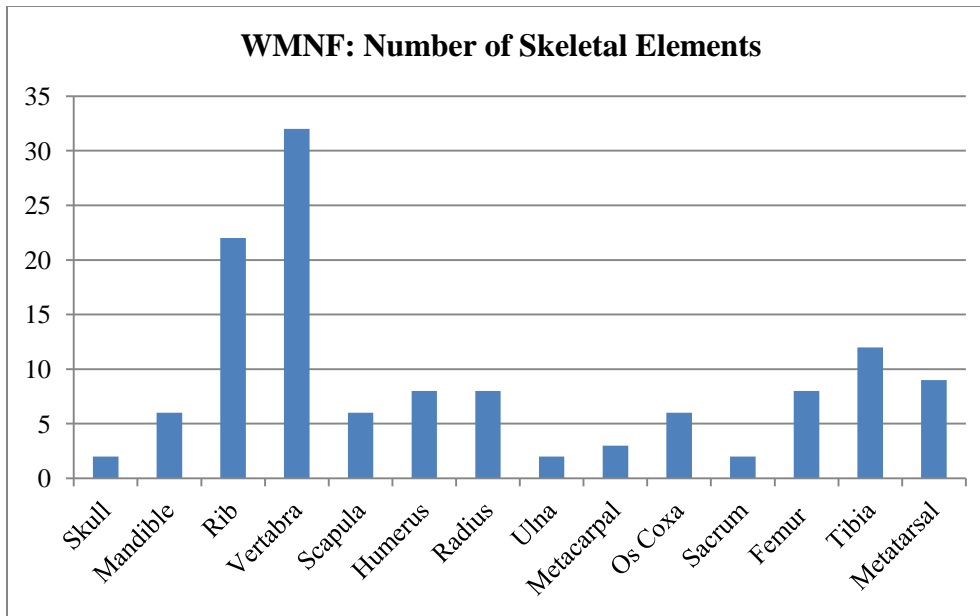


Figure 3.5. Total number of moose skeletal elements documented in the WMNF study site. Totals ignore temporary surges in bone counts due to fresh carcass dumps.

A taphonomic checklist (Pokines 2010) was initially used as a guideline for recording data, including bone weathering stages, presence of soft tissue and decomposition, color staining, carnivore activity, rodent activity, entomological activity, and surface erosion. The extent of weathering was determined based on the six stages established by Behrensmeyer (1978) (Table 2.1). The most advanced weathering stage covering an area larger than 1 cm² was recorded, and shafts of limb bones, flat surfaces of jaws, pelvis, vertebrae, and ribs were used (not edges of bones or areas where there is evidence of physical damage). The position of the bones was not altered by the author throughout the project, and the bones were not secured from scavengers in order to maintain the natural environmental processes these bones have already encountered.

Local weather was recorded on a daily basis to obtain temperatures and precipitation using a weather station located approximately 4.0 km (2.5 mi) northwest of the site at an elevation of 487 m (1600 feet) above mean sea level (amsl) (61 meters below that of the dump site). A HOBO pendant temperature data logger was also placed directly at the site from April 2012 through October 2012 to determine if there was a difference in temperature between the site and the location of the weather station. One Bushnell Trophy Cam™, a motion-sensitive, infrared video camera, was also placed at the site in May 2012 until October 2012 to document scavenger activity.

Multiple soil samples were taken adjacent to the bones and from the surrounding area to determine pH levels. One water sample was also taken from the seasonal drainage that runs through the site. Soil samples were taken from all A, B, and C horizons when applicable and placed in individual plastic bags. Datum points of each soil sample location were documented using a Garmin GPS unit and are accurate up to plus or minus a maximum of seven meters. The samples were then heated and dried using a Cole-Parmer laboratory oven at 100-105° Celsius for 24 hours to ensure that pH analysis of all samples began with the same oven-dry moisture content. The soil was screened using a 2.0 mm Newark Wire Cloth Company standard test sieve in order to remove larger mineral particles and organic matter from the samples. Soil samples were then measured out to approximately 20 grams for each sample. The samples were mixed using one part soil to two parts (by mass) distilled water, allowed to dissolve for at least ten minutes, then an Oakton pH Testr3 kit (with automatic temperature control) was used to measure pH. All materials were rinsed with distilled water between uses of different

soil samples to avoid cross-contamination. Soil color was recorded using Munsell Soil Color Charts (Kollmorgen Instruments Corporation 1994). Each soil sample was moistened (not to glistening) using distilled water and placed on a white cardboard background. The corresponding color chart was held directly above the soil sample to accurately determine the closest match. Color determinations were made in the laboratory under normal UV lighting.

Analysis of all soil samples revealed strong to moderate acidity throughout the horizons. Soil pH levels ranged from 3.14 to 5.30, with an average of 4.36. The water sample taken from the seasonal drainage that runs west through the middle of the sight revealed a mildly acidic pH value of 6.26. Based on comparison with Munsell Soil Color Charts (Kollmorgen Instruments Corporation 1994), soil color throughout the site was variable and included dark, medium, and light browns, gray-white, and red. The gray-white soil appeared in only two samples as a thin subhorizon of horizon A. The A horizon for all locations was a dark brown color, which can be attributed to the high organic content. Hue notations were either 10YR or 2.5Y, values ranged between two and four, and chroma ranged between one and four. Color notations fell between 10YR 2/1 and 2.5Y 4/2 (Table 3.1).

Experimental Sample: Holliston Outdoor Research Facility

Environmental Analysis

In order to provide a greater sample with known depositional dates, a second taphonomic study was carried out in the town of Holliston in eastern Massachusetts at the

Table 3.1. Soil analysis of the WMNF animal dump site.

<u>Location</u>	<u>Waypoint</u>	<u>Horizon</u>	<u>Depth (cm)</u>	<u>Munsell Color</u>	<u>pH</u>
1	N 44°15'01.0"	A	0-17	10YR 2/1	3.14
	W 71°29'41.8"	A ₁	17-24	2.5Y 4/2	4.45
		C	below 24	10YR 2/1	4.89
2	N 44°15'09.0"	A	0-3	10YR 2/1	4.68
	W 71°29'41.2"	A ₁	3-6	2.5Y 4/2	4.19
		B	6-10	10YR 3/4	4.44
		C	below 10	10YR 3/3	5.12
3	N 44°15'01.6"	A	0-6	10YR 2/1	4.82
	W 71°29'41.0"	B	6-16	10YR 3/3	4.34
		C	below 16	10YR 3/4	5.30
4	N 44°15'02.0"	A	0-14	10YR 2/1	3.36
	W 71°29'40.6"	C	below 14	10YR 3/4	3.62
Water Sample					6.26

Boston University Forensic Anthropology Outdoor Research Facility (ORF). The ORF is located in a mixed deciduous forest on 32 acres of mostly unfenced land. This area is characterized by the Transition Hardwoods-White Pine forest region, which occurs up to 457 m (1500 ft) throughout the lower elevations of the New England upland in northern and central Massachusetts and southern New Hampshire (DeGraaf 2006; Gerhardt and Foster 2002; Tang 2012). The major tree species common to this area include yellow birch, paper birch (*Betula papyrifera*), beech, sugar maple, and red maple (*Acer rubrum*). Throughout this region, hemlock-white pine forest is found on the cooler sites, and white pine is characteristic of the well-drained sandy soils (DeGraaf 2006). Characteristic of a temperate climate, this area experiences hot, humid Summers and cold Winters, and remains wet year-round. The area receives an average precipitation of 1236 mm (48.7 in) and has an average yearly temperature of 9.4° C (49° F). The average date of first frost is October 1, and the average date of last frost is May 15, with an average of 120-150 frost-

free days. Mean annual snowfall for this region ranges from 1219-2032 mm (48-80 in) (DeGraaf 2006; Gerhardt and Foster 2002).

The ORF is located near a recreational area that is used mainly for hiking and running and therefore is subject to some human intrusion. However, private property signs are posted along the property boundaries to deter public trespass. Elevation on site is approximately 57 m (188 ft) amsl. Dense wooded areas, open clearings, streams, and large artificial bogs are all present on-site. Like much of New England, the majority of the landscape had been significantly altered by the mid-1800s for agricultural use, but the agricultural fields subsequently were abandoned, and reforestation has been reshaping the area for the past 150 years (Gerhardt and Foster 2002). In the late 1800s, several cranberry bogs were developed on the land of what is now the ORF. None of the bogs currently produce any cranberry growth due to overgrowth of the vegetation (De La Paz, n.d.). Various areas of the property have been either flattened or dug out, and the soil has been pushed around to form artificial mounds and embankments.

Previous analysis of soil samples taken from the general area revealed a strong to moderately acidic soil throughout all horizons. Soil pH levels ranged from 3.21 to 5.61, with an average of 4.74. The majority of soil samples contained a pH value between 4.0 and 4.9. All but one soil sample having a pH below 4.0 was from the A horizon due to the higher organic acid content/greater degree of leaching of base ions at the topsoil level. A water sample taken from a low area revealed a neutral pH level of 7.02, which was a higher pH than was expected due to the prior land use as cranberry bogs. Soil color in the Holliston ORF was variable and included dark browns, gray, bright red, and yellow.

Soil samples were taken from the A horizon of each microhabitat in which the bones were deposited for taphonomic study, all of which revealed a strong to moderately acidic soil. Soil pH levels ranged from 3.77 to 4.90, with an average of 4.21. Based on comparison with Munsell Soil Color Charts (Kollmorgen Instruments Corporation 1994), soil color of the A horizons in each microhabitat were consistently dark brown due to the high organic content, ranging from 10YR 2/2 to 2.5Y 3/2 (Table 3.2).

Scavenging species that have been identified on-site include coyotes, turkey vultures (*Cathartes aura*), red fox, opossum (*Didelphis virginiana*), raccoons, fisher, and domesticated dog. Vegetation specific to the ORF includes white oak (*Quercus bicolor*), paper birch, eastern larch (*Larix laricina*), Norway maple (*Acer platanoides*), white pine, pitch pine (*Pinus rigida*), white spruce, broad-leaved cattail (*Typha latifolia*), and skunk cabbage (*Symplocarpus foetidus*).

Microhabitat Site Descriptions

Three microhabitats were studied, including open grassland, wetland margin, and mixed deciduous forest (Figures 3.6-3.8). The grassland site is located at N 42° 12' 26.8" W 71° 25' 06.7" on the northwest side of a fenced-in decomposition field. Vegetation for this microhabitat consists mostly of bunch grass (*Arundinoideae*) with a wooded area located approximately 4 meters northwest of the site. The wetland margin site is located at N 42° 12' 24.3" W 71° 25' 04.5" in an abandoned, mostly dry cranberry bog at the base of an artificial berm. A seasonal drainage is located one meter southwest of the site. Vegetation located in this microhabitat consists primarily of skunk cabbage and yellow

Table 3.2. Soil analysis of microhabitat sites at Holliston ORF.

Location	Waypoint	Horizon	Depth (cm)	Munsell Color	pH
Grassland	N 42°12'26.6" W 71°25'06.8"	A	0-5	2.5Y 3/2	4.9
Wetland Margin	N 42°12'24.4" W 71°25'04.5"	A	0-5	10YR 2/2	3.96
Forest	N 42°12'19.2" W 71°24'59.2"	A	0-5	10YR 2/1	3.77
Water Sample	N 42°12'24.3" W 71°25'05.1"				7.02



Figure 3.6. Holliston ORF, grassland microhabitat, facing northwest, June 2012.



Figure 3.7. Holliston ORF, wetland margin microhabitat, facing south, June 2012.



Figure 3.8. Holliston ORF, forested microhabitat, facing east, June 2012.

birch. The forested site is located at N 42° 12' 19.1" W 71° 24' 59.4" in a mixed deciduous and coniferous forest, comprised mostly of yellow birch, white pine, and spinulose wood fern (*Dryopteris carthusiana*).

Data Collection

Eighty-seven deer bones were purchased from Pioneer Butchering located in eastern Massachusetts. Skeletal elements included femora, tibiae, humeri, radii, and ulnae. The bones were stored at the point of purchase in a freezer until pickup and were again stored in a freezer at the Holliston ORF until deposited in the field. All bones were cleaned by the butcher, but some soft tissue remained. This state of defleshing is similar to that reached at the end of decomposition or consumption of most of the soft tissue and as such represents a typical state in which isolated, scattered skeletal remains are introduced into the environment shortly after initial feeding. All butchery damage was documented and photographed prior to field experimentation in order to distinguish taphonomic changes from prior damage.

The deer bones were deposited in each microhabitat and secured in place using stakes and wire to prevent loss of data. Thirty-one deer bones were placed in the grassland microhabitat, 28 in the wetland margin, and 28 in the forested area. The number of skeletal elements represented in each microhabitat is displayed in Figure 3.9. Five anchoring stakes were set in each microhabitat, with five to six bones attached to each stake within a 10-x-10 m area. Each skeletal element was numbered for identification using aluminum tags secured to the wire. One Bushnell Trophy Cam™, a

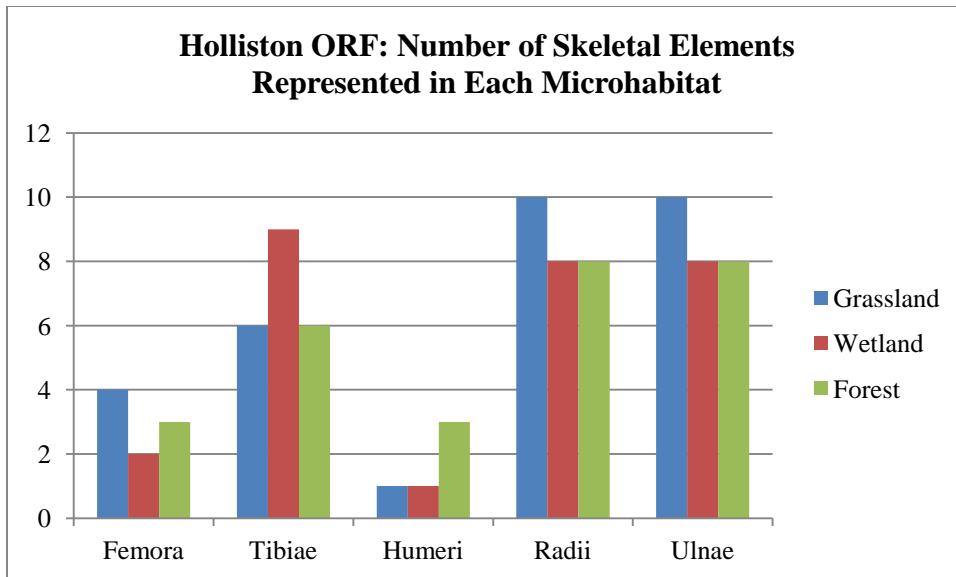


Figure 3.9. The number of skeletal elements (white-tailed deer) represented in each microhabitat at Holliston ORF.

motion-sensitive, infrared video camera, was set up in each microhabitat to monitor scavenger activity. An onsite weather station located adjacent to the grassland site was used to record daily average temperatures and precipitation. HOBO pendant temperature data loggers were also placed in each microhabitat in July 2012 to determine if there was a difference in temperature between the sites and location of the weather station.

Taphonomic data recorded was the same as outlined above for the carcass dump site sample, including bone weathering stage, presence of algae and soil staining, carnivore damage, and rodent gnawing. Observations were made biweekly for the first month, followed by monthly for the remaining time frame.

Statistical Analysis

Once all data were collected, a chi-square test was used to determine if a statistically significant relationship exists between the rate of weathering and microhabitat. A correlation analysis was also conducted between the weather station and temperature pendants to determine if there was a statistically significant difference in temperature.

CHAPTER 4: RESULTS

White Mountain National Forest, New Hampshire

Environmental Analysis

The conditions of the skeletal remains were observed and documented throughout a ten-month period, beginning in December 2011 and ending in October 2012. A correlation analysis was conducted for the weather station (located 4 km northwest of the site) and the temperature pendant placed at the study site. This revealed a significant correlation between the monthly high temperatures ($r=0.943$, $p=0.004$) and a significant correlation between the monthly low temperatures ($r=.979$, $p=0.001$). Thus, the average monthly temperatures for the site location during the months in which the temperature pendant was not in place (December 2011 through March 2012) were estimated based on an average magnitude difference of -2°C (Figure A.1). The coldest month was January with an average temperature of -10°C (14°F), and the warmest month was July with an average temperature of 24°C (75°F). The total number of days in which the site experienced temperature fluctuations above and below freezing was 81, which mostly occurred during December, March, and April. The total precipitation throughout this study was about 725 mm, with May, June, and August each experiencing over 100 mm of precipitation (Figure A.2). Beginning in January 2012, the skeletal elements remained covered by at least 30 cm of snow which persisted through March. By April, the snow had melted, and the elements were exposed.

Osseous Weathering

The time of deposition was unknown for most of the skeletal elements analyzed; however, the NHFG personnel have been dumping animal carcasses at this location for at least 15 years. The initial weathering stage observed for each skeletal element was documented, along with any monthly changes that were noted. Additionally, three fresh moose carcasses were dumped during the study, providing remains with known deposition dates.

The first observations occurred in early Winter (December 2011) and yielded data on 85 isolated moose skeletal elements. At this time, 15% of the bones were in WS 0, 65% were in WS 1, 19% were in WS 2, and 1% were in WS 3. None of the bones observed had reached WS 4 or WS 5. Weathering data could not be collected again until the end of April 2012 due to snowfall covering the bones and making the area inaccessible (and the bones likely completely buried, given the altitude). At this time, all but five bones could be relocated. Ten bones initially observed in WS 1 had progressed to WS 2. This may be due to freeze/thaw cycles occurring directly before and after consistent snow coverage. All other bones observed at this time remained in the initial weathering stage documented. Most bones were again exposed to some direct sunlight until June, when the vegetation grew denser. Observations made in August 2012, 36 weeks after the start of the study, revealed that all bones originally documented in WS 0 (n = 13) had advanced to WS 1. The most recent moose deposition that had occurred prior to the start of the study took place in August 2011. Therefore, it is likely that all bones had reached WS 1 within one year.

Observations of the original sample made at the end of the study (46 weeks later) revealed that 35% of the skeletal elements showed one stage of weathering progression, while the remaining 65% revealed no weathering stage progression. Of the bones that showed progression of weathering stages, 23% progressed from WS 0 to WS 1 and 77% progressed from WS 1 to WS 2. The skeletal element initially observed in WS 3 did not show any weathering advancement. None of the elements advanced more than one additional weathering stage. Figure 4.1 outlines the progression of weathering documented during each monthly observation.

Forty-one bones (mostly ribs and vertebrae) were added to the sample throughout the study. These bones were added from three freshly dumped moose carcasses with known dates of deposition. The PMI at the end of the study for each carcass was five, three, and one month. Five of these bones (all long bones) from the first moose reached WS 1 by the end of the study, five months after death. The remaining bones (ribs and vertebrae) from all carcasses revealed no signs of weathering after one to five months PMI. Further taphonomic changes of these remains are described later in this chapter.

Lichens, Moss, and Algae

Lichens growth was not observed on any of the skeletal remains throughout the study. The presence of moss observed on the bones remained consistent and was noted on 28% of the skeletal elements. Initially, green algae were observed on 74% of the skeletal remains. This increased to 85% in April with the first site visit following snow melt. Excluding the bones added throughout the study from freshly dumped moose

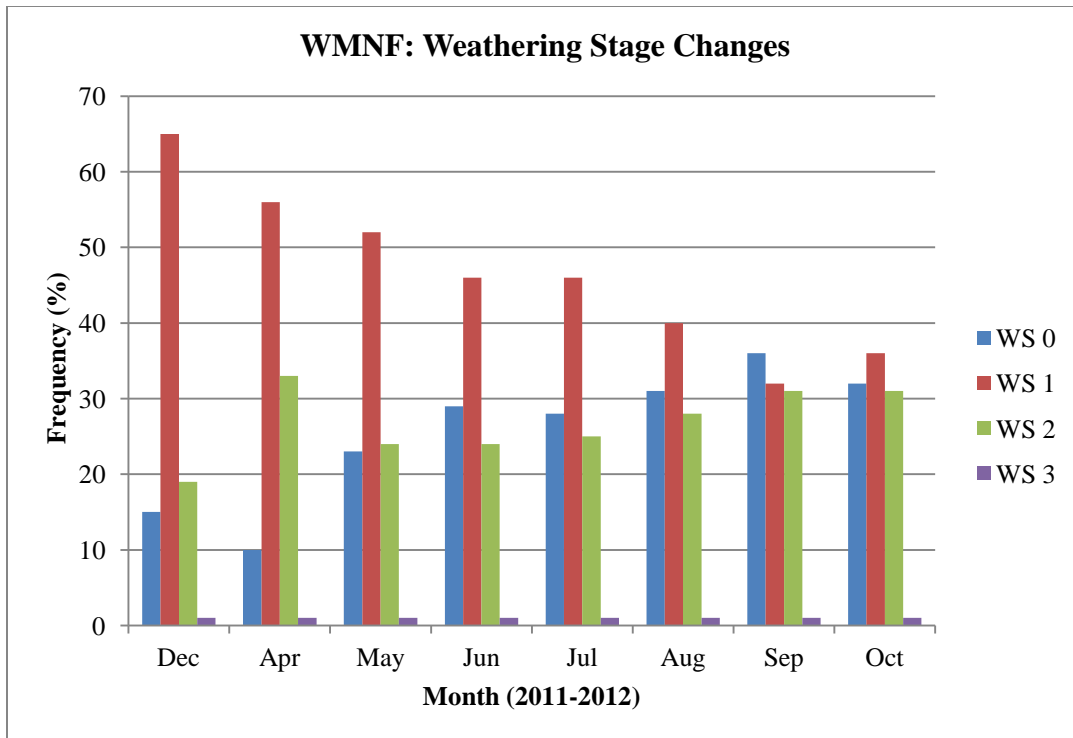


Figure 4.1. Weathering stage progression throughout the study period, beginning in December 2011 and ending in October 2012. No elements in WS 4 and WS 5 were observed. The increases in WS 0 are due to the fresh skeletal elements added throughout the study.

carcasses, the percentage of bones on which algae was observed remained relatively consistent (between 80-85%) throughout the next three months. From July through October, most bones (90%) showed at least slight algae growth. Algae was more prominent on bones located adjacent to the creek and was commonly observed along the margins, growth centers, and epiphyses of bones, although it was occasionally observed as patchy segments across the surface of the bone. Neither lichens nor moss were observed on any of the skeletal remains added to the sample from the three fresh moose dumps (n=41). Five of bones (all long bones) from the moose dump observed in May

revealed slight algae growth on the epiphyses 27 days after death. Algae were not observed on any of the remaining elements (Table 4.1).

Color Staining

Algae and soil staining were common sources of discoloration observed on the bones. Discoloration due to decompositional fluids was not seen on any of the remains. Brown soil staining, however, was observed on most of the skeletal remains. It was initially observed on 92% of the bones, and increased to 97% by the end of the study. Soil staining occurred as either patchy segments or consistently along the diaphysis on the underside of the bone. All of the bones added in May and June from the first moose dump revealed patchy or consistent soil staining on the bottom surface at a PMI of 27 days.

Carnivore and Rodent Gnaw Marks

Of the skeletal elements that showed carnivore damage (33%), pits, punctures, scores, and furrows were all observed. Scores were the most common and were observed on 65% of the bones, followed by punctures observed on 19%, pits observed on 15%, and furrows observed on 1%. Multiple types of tooth marks were seen on several of the bones. Tibiae and femora had the highest frequency of carnivore marks, while vertebrae, ribs, and metatarsals revealed the lowest frequencies. Skeletal elements that contained a sample size less than five (crania, ulnae, metacarpals, and sacra) were left out of the frequency comparison analysis. Gnaw marks appeared mostly on the proximal end of

Table 4.1. The number of bones observed with algae growth on a monthly basis in the WMNF. The number of bones observed monthly was inconsistent due to loss of bone and the addition of new bones from fresh moose carcasses. Only five of the new bones revealed any algae growth during the study.

Month	Weeks Elapsed	Total Bones Observed	Algae
Dec 2011	0	85	63
Apr 2012	19	80	68
May 2012	25	82 (15 new)	55
Jun 2012	29	71 (5 new)	42
Jul 2012	32	57	32
Aug 2012	36	105 (13 new)	67
Sep 2012	41	113 (8 new)	67
Oct 2012	46	113	68

long bones, with the epiphysis occasionally gnawed off, exposing the medullary cavity.

Carnivore damage and tooth marks observed on ulnae were typically seen on the

olecranon process, which is a similar pattern seen at the Holliston ORF (see below).

Rodent gnaw marks were observed on 6% of the bones (n = 7), occurring mostly on

pelves (Figure 4.2) and the anterior border of scapulae. The rodent gnaw marks followed

previously documented patterns (Haglund 1992; Pokines and Tersigni-Tarrant 2012),

appearing as parallel grooves on slightly weathered bone.

Scavenging and Dispersal Patterns of Freshly Dumped Moose

Throughout the course of this study, three additional road-kill moose were

dumped in May, July, and September. There was no reporting nor observation of any

white-tailed deer or other animals dumped during this time.



Figure 4.2. Large rodent or lagomorph gnawing along the border of an acetabulum; also note the presence of weathering and algal and soil staining, WMNF.

First Moose Deposition: May 2012

The animal remains for this deposition were not observed until thirteen days postmortem. The head and portions of the thorax and vertebral column were located approximately 20 meters west-northwest of the primary dumping site. The remains appeared as if they were dragged down a 15° slope and into a thick vegetated area. The bones were mostly articulated and partially covered by desiccated skin. The soft tissue and organs of the abdominal region had been removed (Figure 4.3). The portions of exposed bone did not retain any soft tissue, were still greasy, and showed no signs of weathering. Blow flies (*Calliphoridae*) were still very prevalent, and the odor was strong.



Figure 4.3. Moose remains deposited in May; the PMI was 13 days.

Five long bones (two radii, one femur, one ulna, and one tibia) that had been scattered were located approximately 40 meters south-southwest of the primary dumping site and were tagged for further taphonomic observation. These bones were still fresh and were not previously located and were therefore presumed to be from the same carcass. These long bones revealed carnivore scores on the epiphyses, and the tibia revealed damage on the proximal anterior end, exposing the medullary cavity. The other long bones from this carcass could not be located.

Video footage using an infrared, motion-sensitive camera placed at the site 13 days after death showed the presence of coyotes and turkey vultures consuming the remains of the head, neck, and thorax. A single coyote was seen feeding for four consecutive days beginning 13 days after death, and then it returned every few days for

the next ten days. The coyote was observed throughout the day and night. Two turkey vultures were observed feeding for a single day 14 days after death. The initial scavenging that had occurred following the moose dump could not be documented using video recordings.

Patchy soil staining on the bottom surface of the long bones and slight algae staining on the epiphyses was observed the following month (27 days later). The desiccated skin covering the thorax and vertebral column was no longer present. Segments of the vertebral column had been disarticulated, but the ribs and vertebrae remained in the same general location. No soil or algae staining nor carnivore damage was observed on the ribs or vertebrae. At the end of the study (142 days after the moose deposit), all long bones had reached WS 1, while the ribs and vertebrae remained in WS 0.

Second Moose Deposition: July 2012

The animal remains for the deposition that occurred in July were observed at 2 days postmortem. The moose was located on the hillside of the primary dumpsite. The thorax and abdominal region were split open, most likely due to a vehicle collision, with the intestines displaced from the abdominal cavity. The rest of the carcass was intact (Figure 4.4). Blow flies were present throughout the carcass. No maggots were observed, and no carnivore activity appeared yet to have taken place. A video camera placed about 3 m from the carcass confirmed the lack of scavengers. The odor was moderate compared to the last moose dumped in May.



Figure 4.4. Moose remains deposited in July; the PMI is 2 days.

Analysis of video recording over the next month revealed black bear, coyote, and raven scavenging. The black bear began feeding on the carcass on the third night, and the coyote began feeding later that same night. A black bear was observed feeding for only 2 consecutive days then did not return to the carcass, while a coyote was seen feeding throughout the entire process. A raven was seen on a single occurrence on day 4, feeding on the abdominal region. Both the black bear and coyote fed on the ventral thorax first, followed by the neck (Figure 4.5). On day 7, the coyote was seen tugging on the upper and lower extremities. The lower extremities were removed first on day 7, followed by the upper extremities on day 8. The entire carcass had been consumed and/or scattered by nine days following deposition.



Figure 4.5. Black bear feeding on the ventral thorax of a moose; the PMI is 3 days.

Two ribs were located on top of the hillside, about 7 meters east of the initial carcass location. However, the majority of ribs and vertebrae that were located remained within a few meters of the original location. Additionally, one humerus was located about 36 m southwest of the initial carcass site, and one metacarpal and one metatarsal were located about 45 m southwest of the initial site. No weathering or discoloration (soil or algae staining) were observed on these remains. Overall, 90% of the total skeletal elements could not be relocated.

Third Moose Deposition: September 2012

The final moose deposition during this study occurred in September 2012 and was observed after a PMI of ten days. By this time, the animal remains were all either

consumed or scattered. Scavenging data were collected based on video recordings; however, the entire scavenging process did not get recorded. Some of the ribs and segmented vertebral column were located within a few meters of the initial dump location, but the remaining skeletal elements could not be relocated among the dense vegetation.

Video footage revealed scavenging of the remains by black bear, coyote, ravens, and turkey vultures. A single coyote was first observed feeding on the dorsal region of the moose on day two following the dump. The coyote continued to feed on the moose for at least three more consecutive nights, disarticulating the head on day four then continuing to feed on the dorsal region. At one point, two coyotes were seen feeding on the moose simultaneously, but this only occurred on one of the nights for a brief time. On day three, a black bear was also seen feeding on the dorsal region of the moose but moved to the head and dragged the moose approximately one meter across flat ground. The black bear was only observed one day. Later that same night after the bear left, a coyote was seen feeding on the head. Three days after death, two ravens and a turkey vulture were first observed feeding on the dorsal region of the moose and the ravens returned for three consecutive days. The turkey vulture was observed feeding one other time three days later. The video camera did not record any further footage past this point. Disarticulation of the extremities could not be observed. However, it is clear that all significant exterior soft tissue had been either consumed or scattered by day ten.

Scavenging Summary of Fresh Moose Deposits

Throughout this portion of the study, taphonomic observations were made on three fresh, whole-carcass moose depositions. Common scavengers that were observed on video cameras include black bear, coyote, raven, and turkey vulture. The scavengers were seen feeding on the carcass at different times and for different durations. Coyotes were observed most frequently and were commonly seen feeding until the carcass was gone. Black bears tended to appear earlier in the process and feed for only one or two days (Table 4.2). Whole carcasses had been completely scattered and consumed in as little as nine days. Following consumption of the organs and thoracic region, the extremities were typically removed and dragged up to 45 meters from the original site. The remaining ribs and segments of the vertebral column were generally located within a few meters of the original site (Table 4.3).

Holliston Outdoor Research Facility

Environmental Analysis

The condition of skeletal remains was observed and documented throughout a 50-week period, beginning in February 2012 and ending in February 2013. A correlation analysis was conducted for the on-site weather station and each temperature pendant in order to determine if there was a significant difference in temperature between the areas. This revealed a significant positive correlation between the monthly high temperatures for each microhabitat and the weather station data (grassland: $r = 0.966$, $p = 0.034$;

Table 4.2. Timing of scavenger activity at the WMNF site based on observations of one freshly dumped moose carcass in July. The other two fresh moose carcasses were omitted from this table due to lack of video footage. Scavengers were observed using motion-sensitive infrared video cameras.

Scavenger	PMI of moose carcass(days)	Number of Days Observed	Patterns and Observations
Coyote (<i>Canis latrans</i>)	3-9	7	Coyotes were observed most often and were seen on a daily basis. Two coyotes were seen feeding at once on one occasion
Black bear (<i>Ursus americanus</i>)	3-4	2	Black bears were only observed feeding for 2 consecutive days then did not return
Raven (<i>Corvus corax</i>)	4-7	1	Ravens feed on the carcass in pairs or alone

Table 4.3. Scavenging patterns from three fresh moose carcasses that were deposited in the WMNF site. Data were supplemented by use of motion-sensitive infrared video cameras.

Month of Moose Deposition	Number of Days for Carcass to be Consumed/Scattered	Scavengers Observed	Consumption and Disarticulation Patterns	Dispersal Patterns
May 2012	28	Coyote and turkey vultures	The extremities had been disarticulated and the organs were consumed by the first observation, 13 days after death. Desiccated skin covered the thorax, which was consumed over the next 15 days.	The head, neck, and thorax were dragged 20 meters from the original location then remained in that area. The extremities were scattered up to 40 meters from the original location.
July 2012	9	Black bear, coyote, turkey vultures, and ravens	Ventral thorax was consumed first, followed by the neck, lower extremities, and upper extremities.	Most ribs and vertebrae observed remained within a few meters of the original location. The extremities were located 36-45 meters from the original location.
September 2012	10	Black bear, coyote, turkey vultures, and ravens	Dorsal region was consumed first, followed by the neck and head. Disarticulation of the extremities could not be observed.	Most ribs and vertebrae observed remained within a few meters of the original location. The extremities and head could not be located.

wetland: $r = 0.993$, $p = 0.007$; forest: $r = 0.993$, $p = 0.007$) and a significant positive correlation between the monthly low temperatures for each microhabitat and weather station data (grassland: $r = 0.995$, $p = 0.005$; wetland: $r = 0.994$, $p = 0.006$; forest: $r = 0.994$, $p = 0.006$). Thus, the average monthly temperatures for each microhabitat during the months in which the temperature pendants were not in place were estimated based on an average magnitude difference (Figures A.3 and A.4). The temperatures for the

wetland and forest microhabitats were consistent with the weather station. However, the average monthly highs for the grassland microhabitat were consistently 6° C warmer, and the average monthly lows were 1° C warmer. Overall, the coldest month was January 2013 with an average temperature of -3° C, and the warmest month was July with an average temperature of 23° C. The total number of days in which the site experienced temperature fluctuations above and below freezing was 86, which mostly occurred during November and December (20 and 18 days, respectively). The total precipitation throughout this study was 755 mm, with April, May, June, and December each experiencing around 100 mm of precipitation (Table A.5). The skeletal remains were observed once covered by snow in early March, which lasted no more than two weeks. Minimal snow coverage occurred again in December, but did not accumulate more than three inches.

Loss of Soft Tissue Remnants

Although all skeletal elements were cleaned by a butcher, some soft tissue (including connective tissue and muscle) remained. Thus, several skeletal elements were still articulated at the time of bone deposition in each microhabitat. The loss of remaining soft tissue occurred slowest in the grassland site and fastest in the forested site. In the grassland site, substantial loss of remaining muscle, flaking of periosteum, and desiccation of ligaments was observed by four months after deposition. However, by the end of the study, ligaments were still present and some of the bones were still held together by soft tissue. In the wetland margin, loss of most ligaments and muscle

attachments occurred by four months after deposition, and none of the bones that were initially articulated remained intact by the end of the study. Lastly, the bones in the forested site revealed substantial loss of soft tissue three months after deposition and was completely absent by the fourth month. Previously articulated bones had become disarticulated by this time. However, this site received the most amount of scavenger activity which first occurred two months after deposition. Desiccation of soft tissue was most notable in the grassland site.

Osseous Weathering

Weathering was first observed on two of the bones located in the forested site in July 2012, about five months after the bones were placed in each microhabitat. WS 1 was first observed in the grassland site and wetland margin the following month. Throughout the study, the bones in the forested site continued to reveal the most advanced weathering, followed by the grassland and wetland margin. The percentage of bones noted in WS 1 each month is presented in Figure 4.6. The highest percent of increase from WS 0 to WS 1 occurred between September and October in each microhabitat. This may be due to temperature fluctuations above and below freezing typical this time of year. Observations made in February 2013 (50 weeks after deposition) revealed slight changes in weathering. In the grassland site, the percentage of bones observed in WS 1 increased from 35% to 39%, the percentage of bones in WS 1 in the forested site increased from 44% to 48%, and the percentage of bones in WS 1 remained the same in the wetland site. None of the bones progressed past WS 1;

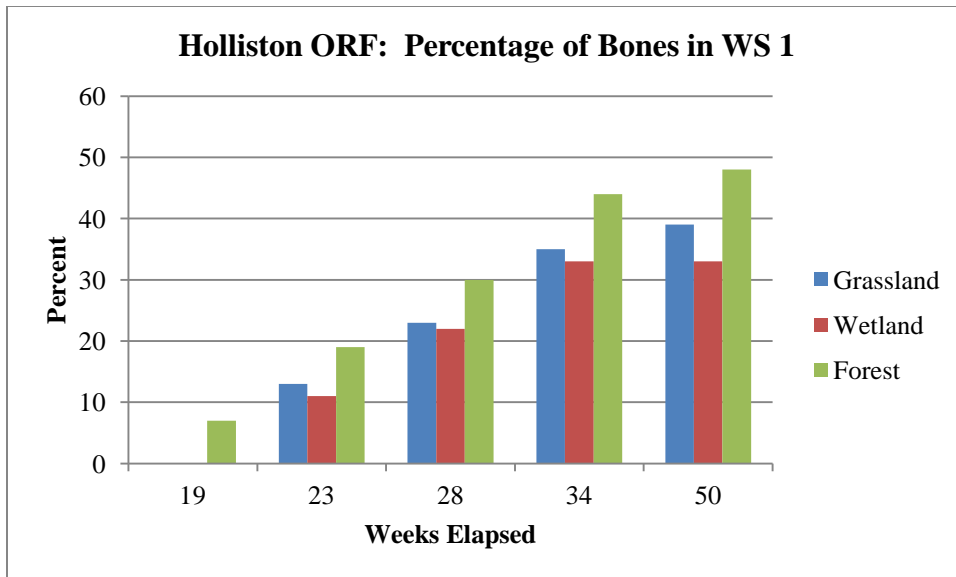


Figure 4.6. This graph represents the percent of skeletal elements observed in WS 1 for each microhabitat beginning in July 2012. WS 1 was first observed 19 weeks after deposition. None of the bones had progressed past WS 1.

therefore, a chi-square test was used to determine if microhabitat was a factor in weathering over this interval. A chi-square test revealed that microhabitats were not a statistically significant factor in osseous weathering when examined 11.5 months after deposition ($\chi^2 = 1.26$; $p = 0.53$). However, a larger sample size and a longer duration of study may suggest that the microhabitats significantly influence the rate of weathering.

Weathering cracking of the long bones in each site followed a longitudinal pattern parallel to the diaphysis (Figure 4.7). Weathering was first noted as small linear cracks, progressing into deeper, longer cracks. The bones placed in the forested site revealed more pronounced cracking, while the bones placed in the grassland and wetland margin revealed slighter, less pronounced cracking. The majority of the bones located in the grassland and wetland sites maintained some remnants of ligaments. Conversely, there



Figure 4.7. WS 1 of a femur located in the forested microhabitat at Holliston ORF; the PMI is eight months. Note the carnivore damage located on the proximo-lateral end (red arrow).

was no remaining soft tissue observed on any of the bones in the forested site. All of the bones in each microhabitat retained residual greasiness.

Significant vegetation and environmental changes were observed throughout the study in each microhabitat, affecting the amount of sun exposure and moisture content of the bones. This may account for the differences among weathering observations. By June 2012, the bones placed in the grassland site were protected from sun exposure by tall bunch grasses, which grew over one meter high and continued to shade the bones throughout the rest of the study. The forest floor of the wetland margin was covered by skunk cabbage and other plants for approximately three months, offering protection from sun exposure. Additionally, increased amounts of precipitation during the Summer

resulted in partial or full submersion of half of the bones located in the wetland margin beginning in late June and persisting throughout the rest of the study. In the woodland site, the bones became partially shaded during the Summer by deciduous trees. However, the vegetation coverage of the forest floor remained relatively minimal. Thus, the bones located in the forested microhabitat seemed to have received a greater amount of sun exposure throughout the entire study. Overall, the results indicated that microhabitat was not a significant factor of osseous weathering after 11.5 months of exposure. Weathering was more influenced by time and seasonality. Microhabitat would likely have a more significant effect over a longer period of exposure.

Lichens, Moss, and Algae

The presence of algae was mostly observed on bones located in the wetland margin and was first seen on 15% (n=4) of the bones at this site 16 weeks after deposition. The presence of algae observed in the wetland margin continued to increase throughout the study, especially as some of the bones at this site became partially or fully submerged in water (late June through February). By September (28 weeks after deposition), algae was observed on 44% of the bones at this site, and increased the following month to 52%. At this time, the vegetation in this area was not as dense, and sunlight exposure was stronger. By the end of the study in February 2013 (50 weeks after deposition), algae was noted on 70% of the bones in the wetland margin.

Conversely, algae were not observed on any of the bones in the grassland microhabitat until 34 weeks after exposure, and were never observed on the bones in the

forested site. Algae was first observed on only 16% of the bones in the grassland in October. However, this increased to 64% by the end of the study in February 2013 (50 weeks after deposition) (Figures 4.8 and 4.9). These rates appear to be much slower in Holliston than in the WMNF. In the WMNF, algae were first observed on the fresh moose remains 4 weeks after deposition.

Color Staining

Bone discoloration was first observed approximately two and half months after deposition. Patchy dark brown staining along the diaphyses due to soil contact was noted in all three microhabitats. Additionally, dark reddish gray to white discoloration due to the decomposition of remaining soft tissue on skeletonized remains was first observed at this time in the grassland and wetland sites. As the study progressed, the skeletal elements in the grassland and wetland margin continued to display the highest amounts of bone discoloration, resulting from soil, algae, and decomposition. Conversely, the skeletal elements in the forested site only continued to show signs of soil staining (Figure 4.10). Bleaching was first observed in the forest and grassland sites three months after deposition, although cracking was not initiated until five and six months after deposition, respectively. Bleaching was observed in the wetland margin after four months, and cracking was first initiated after six months.

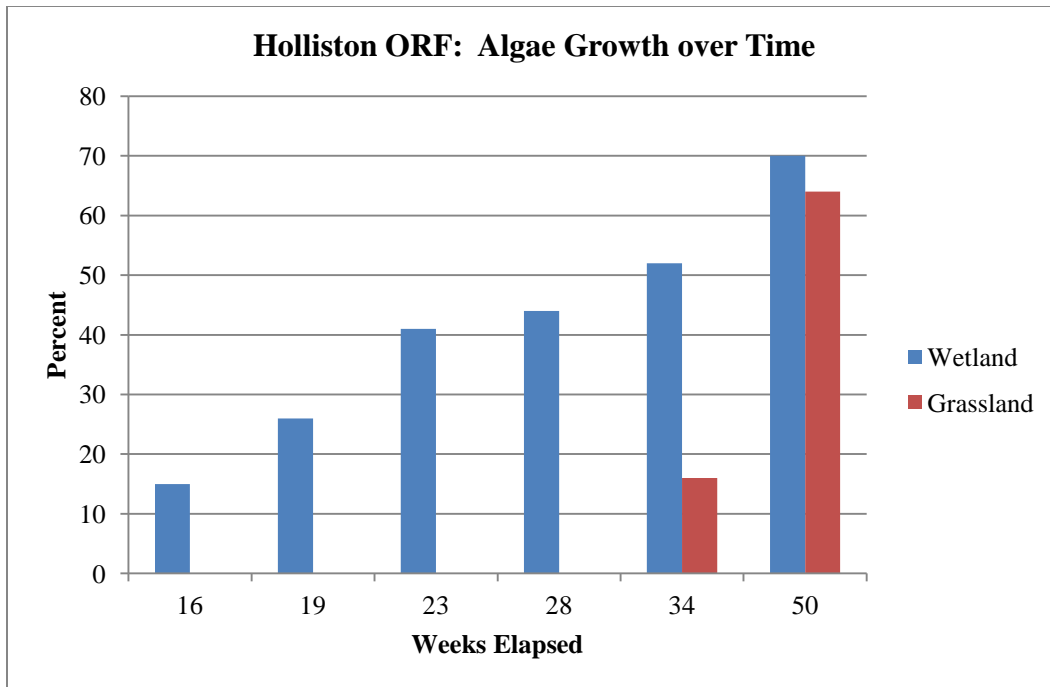


Figure 4.8. The percentage of bones displaying algae growth in each microhabitat and how that changed throughout the study. Algae was never observed on the bones in the forested site.



Figure 4.9. Example of algae growth 50 weeks after deposition in the grassland microhabitat. Scale is in mm.



Figure 4.10. Difference in color changes observed between microhabitats in Holliston 28 weeks after deposition. The elements in the grassland (A) and wetland (B) experienced more drastic color changes than elements in the forest (C).

Scavenging and Gnaw Marks

Common scavengers that were observed on the motion-sensitive video cameras include coyote, fox, fisher, and opossum. The amount of scavenging and temporal span varied between sites, with the forested site displaying the most scavenging. This was reflected on the video cameras and the frequency of gnaw marks evident on each bone (Figure 4.11). However, the first sign of scavenging caught on the video camera was a great horned owl (*Bubo virginianus*) in the grassland site. This single event occurred five days after deposition when the bones were covered by about 15 cm of snow. The owl was observed pecking at the bone and attempted to fly off with it. A coyote was also observed gnawing and tugging on bones in the grassland site three months after

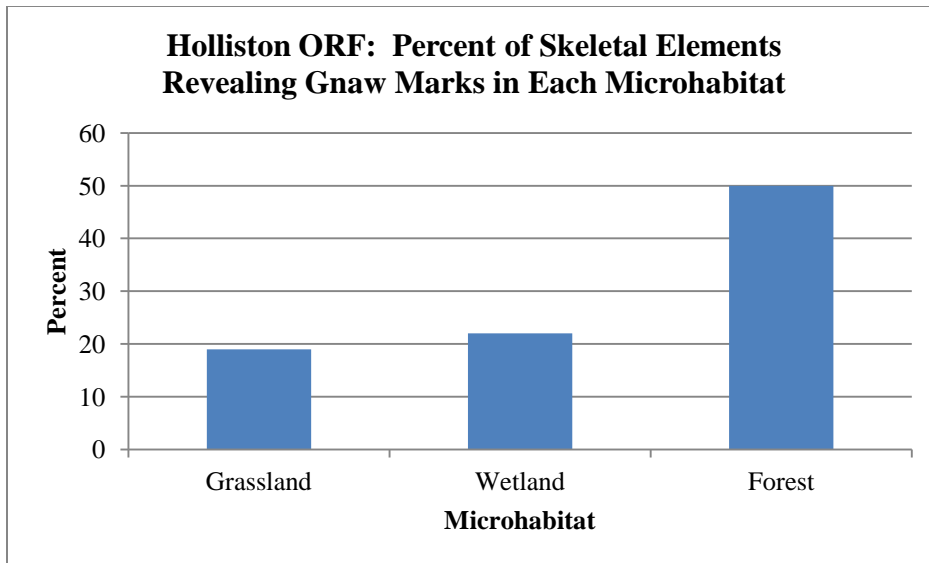


Figure 4.11. This figure represents the percentage of skeletal elements in each microhabitat showing carnivore gnaw marks.

deposition, in the same manner that domesticated dogs gnaw on rawhides. The coyote held the diaphysis of the bone between his two front paws and gnawed on end of the bone. This was also a single occurrence that took place at night and no other signs of scavenging were observed following the coyote in this microhabitat. White-tailed deer were seen in the videos displaying curiosity and smelling the bones, but were not observed gnawing on any of the bones.

In the wetland margin site, the first sign of scavenging occurred about a month after deposition, when a fisher was seen gnawing on the bones. The fisher was observed gnawing on the bones two other nights, two days apart, but was not seen past this time. A coyote was observed gnawing and tugging on multiple bones three separate nights in May, about three months after deposition. However, it did not appear at this site again throughout the study. The coyote appeared more aggressive with bones and gnawed on

them for longer time spans than the fisher. Additionally, a raccoon was first observed gnawing on the bones about seven months after deposition, returning one other night the following month. All animals were observed gnawing on the bones during the night individually. Deer and domesticated dog present at the site did not show any interest in gnawing on the bones.

Scavenging was most prevalent in the forested site, although the first scavenging event did not occur until two months after deposition. At this time, a coyote was observed gnawing and tugging on the bones for two consecutive days, followed by a third day about one month later. Opossum frequently visited the site to gnaw on the bones, beginning three months after deposition and occurring for five consecutive days, followed by nine other events spread out until mid-August. A fox was observed feeding on the bones on two separate occasions about a month apart, starting around the same time the opossum was first seen. Fisher and raccoon were both seen feeding on the bones on two separate occasions, beginning about four months after deposition. Finally, a fox squirrel (*Sciurus niger*) first visited the site five months after deposition and showed a lack of interest in the bones. However, a fox squirrel was seen briefly nibbling on one of the elements six months after deposition. This time corresponds with the first observation of WS1 in this site. Marks potentially left on the bone from the fox squirrel could not be determined. The type of scavengers and frequency of occurrence are summarized in Table 4.4.

Carnivore gnaw marks observed on the bones were most prevalent in the forested site (50%), followed by the wetland site (22%) and grassland site (19%) (Figure 4.11).

Table 4.4. Timing of scavenger activity at Holliston ORF based on data collected using motion-sensitive infrared video cameras.

Microhabitat and Scavenger	Time of First Occurrence After Deposition	Number of Days Observed	Observations/Patterns
Grassland			
Great horned owl	5 days	1	Bones were covered by 15 cm of snow
Coyote	3 months	1	Singe event
Wetland			
Fisher	1 month	2	Events occurred 2 days apart
Coyote	3 months	3	After the first night, the coyote didn't return for a week then was observed for 2 consecutive days
Raccoon	7 months	2	By this time, 22% of the bones in the wetland had reached WS 1. Events occurred one month apart
Forest			
Coyote	2 months	3	2 consecutive days followed by a third day 1 month later
Opossum	3 months	14	5 consecutive days, followed by 9 separate events throughout the next 3 months
Fox	3 months	2	Events occurred one month apart
Fisher	4 months	2	Events occurred 7 weeks apart
Raccoon	4 months	2	Events occurred 2 days apart
Squirrel	5 months	1	Time corresponds with first observation of WS 1

Considering all skeletal elements regardless of microhabitat, humeri revealed the highest percentage of carnivore gnaw marks (80%), followed by femora (78%), ulnae (38%), and tibiae (24%). Gnaw marks were not observed on any of the radii (Figure 4.12). Gnaw marks were frequently observed on the humeral head, femoral head, and greater trochanter of the femur. All of the gnaw marks that were observed on the ulnae occurred on the olecranon process. Punctures (Figure 4.13), pits, scores, and furrows were all observed in each microhabitat. Punctures and scores were both observed on 17 of the elements, while pits were observed on 11 elements and furrows were observed only on five elements (Table 4.5). Some elements represented multiple types of tooth marks. In comparison to the WMNF, scores were less abundant in Holliston ORF. This may be due to the difference in soft tissue adhering to the remains when deposited between the two areas. The scavenging process of whole-carcass consumption and the tearing of soft tissue from the skeleton in the WMNF, likely resulted in increased scores relative to punctures and pits from gnawing. Gnawing was more commonly noted for longer durations in Holliston.

Entomology

Significant amounts of American carrion beetles (*Necrophila americana*), mostly larvae, were first observed on the bones in late April, two months after deposition (Figure 4.14). The beetles were located mostly on the ground side of the bones and were more abundant in the grassland and wetland margin sites than the forested site. A significant amount of soft tissue loss was observed in association with the beetles. Beetle activity

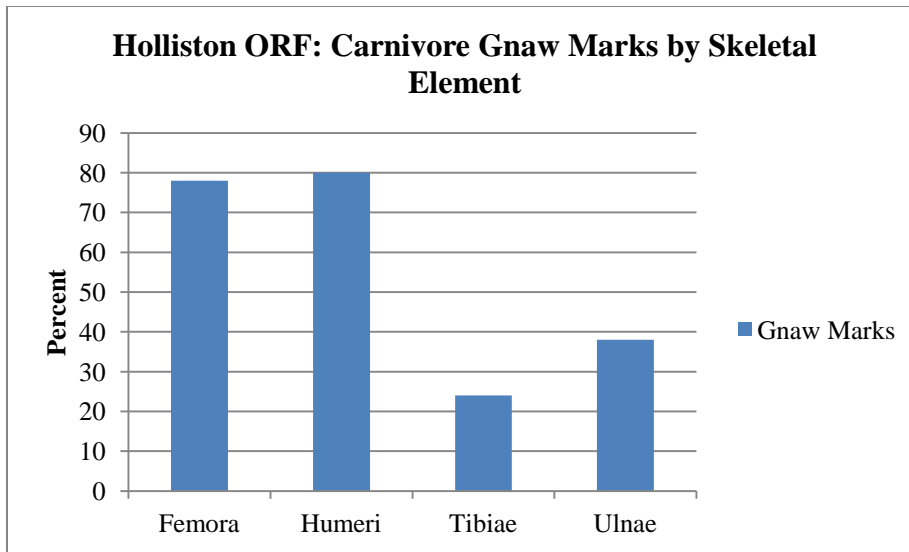


Figure 4.12. The percentage of skeletal elements that revealed carnivore gnaw marks at the end of the study in Holliston ORF. No gnaw marks were observed on any radii.



Figure 4.13. Carnivore puncture marks observed on a femur from the forested microhabitat in Holliston ORF. Puncture marks measure 4 mm wide x 6 mm long and are likely from a medium-sized scavenger. Note the circular appearance, crushed walls, and penetration of the cortical bone.

Table 4.5. Number of skeletal elements in WMNF and in each microhabitat in Holliston ORF that revealed the different types of carnivore tooth marks (pits, punctures, scores, and furrows).

Location	Pits	Punctures	Scores	Furrows
Holliston/Grassland	5	6	6	3
Holliston/Wetland	1	3	5	1
Holliston/Forest	5	8	6	1
WMNF	6	8	27	2



Figure 4.14. American carrion beetle larvae feeding on the soft tissue of an articulated femur and tibia in the forested microhabitat two months after deposition.

persisted for approximately six weeks. During this time, remnants of soft tissue were still present on the remains, monthly precipitation was close to 100 mm, and the average monthly temperature was 13° C. American carrion beetles are known to feed on carrion, fly larvae, and the larvae of other beetles and are typically found directly on remains.

They are active during Spring and Fall, and over the Winter in the adult stage (Byrd and Castner 2010).

CHAPTER 5: DISCUSSION

Weathering

The PMI for most skeletal elements analyzed in the WMNF is unknown, making it difficult to discern weathering rates for this area and develop a comparative analysis. However, continued analysis of this sample will provide more meaningful data. Upon initial documentation of the site, the majority of skeletal elements observed were in WS 1 (65%) followed by WS 2 (19%), WS 0 (15%), and WS 3 (1%). None of the bones observed were more advanced than WS 3 (Figure 4.1). Since Conservation Officers have been dumping carcasses at this location for at least 15 years, it can be posited either that more advanced weathering stages (WS 4 and 5) likely take longer than 15 years to occur, that advanced stages were reached and the bones disintegrated, or that bones deposited earliest were buried under leaf deposition and not recovered. Monthly observations showed that 35% of the bones revealed the progression of one sequential weathering stage during the study, but the time of exposure in the previous weathering stage was unknown. Of the bones that showed progression of weathering stages, 23% progressed from WS 0 to WS 1 and 77% progressed from WS 1 to WS 2. The highest frequency of weathering advancement was noted in Spring (April through May), following snow melt but prior to thick vegetation coverage. None of the elements advanced more than one additional weathering stage.

Skeletal elements that were recovered from three fresh moose dumps that occurred during the study provided a small sample with known depositional dates. Five of the elements revealed WS 1 five months after death. The other elements remained at

WS 0. The elements that displayed WS 1 were deposited early Summer and weathering was first observed early Fall, as daily temperature fluctuations started to occur and vegetation was less dense.

This initial weathering rate is similar to that of other current northern New England taphonomic studies. The sample at Holliston ORF yielded similar results, as WS 1 was first observed in the forested site five months after deposition and in the wetland and grassland sites six months after deposition (Figure 5.1). Although a chi-square test revealed that microhabitats were not a significant factor of weathering over this interval ($p = 0.53$), variations were observed in the initial onset and progression of cracking. Weathering cracks were more pronounced in the forested site than in the other microhabitats (Figure 5.2). This is likely due to the continuous sun exposure in the forested site for part of the year. The skeletal remains in the grassland site became covered by tall, thick bunch grass, and the skeletal remains in the wetland margin were sheltered by skunk cabbage and eventually became submerged in water. Thus, the influence of microhabitat needs to be considered as weathering advances.

Similarly, Sorg (2012) noted WS 1 after six months of exposure on a sample of pig remains placed in a forested, highlands environment in Maine. These results are also comparable to initial weathering rates noted in Amboseli Park, Kenya (Behrensmeyer 1978), Yellowstone National Park, USA (Miller 2009), Nebraska, USA (Fiorillo 1989), and Parc National des Virunga, Zaire (Tappen 1992, 1994, and 1995). Conversely, these results are significantly different than the weathering rates observed in Ituri Rain Forest,

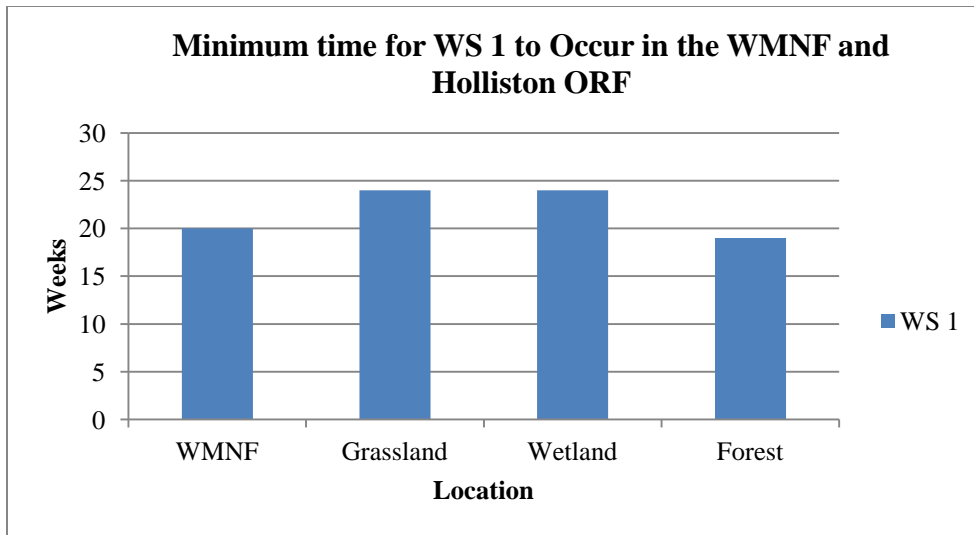


Figure 5.1. Comparison of the minimum number of weeks elapsed after surface exposure for WS 1 to occur in the WMNF and each microhabitat in Holliston ORF.



Figure 5.2. Comparison of WS 1 cracking between the microhabitats. Cracking was less pronounced in the grassland (A) and wetland (B) sites than in the forested site (C).

Zaire (Tappen 1994), in which WS 0 was seen up to 16 years after death on a sample of elephant skeletons (Table 5.1). However, the length of this study is not sufficient for comparison of the later stages of weathering. Furthermore, Miller (2009) noted that while the earlier weathering rates observed were comparable to that of Behrensmeyer (1978), broad differences were noted as weathering progressed into more advanced stages.

Scavenging and Gnaw Marks

Scavenging of the freshly dumped moose in the WMNF occurred in patterns similar to those discussed by Haglund *et al.* (1989) and Haynes (1980) with slight variations. Scavenging was initiated within the first few days and continued until consumption of soft tissue and disarticulation of the extremities was complete. However, the timing and duration of scavenging varied by species. Black bears appeared only to feed on the carcass for the first few days, while coyotes continually returned to the carcass (Table 4.2). The pattern of consumption observed on one of the moose began with the ventral thorax region, followed by the neck and lower and upper extremities. Conversely, the feeding on another moose began with the dorsal region followed by disarticulation of the head. Disarticulation of the extremities occurred later and could not be observed. These variations in scavenging patterns could partially be a result of the vehicle collisions and location of trauma (Table 4.3).

Although the taphonomic observations of Haynes (1980) were associated with kill sites rather than scavenging, similar transport distances and gnaw patterns were observed.

Table 5.1: Comparison of subaerial weathering rate observations in different environments.

Location	Environment	Sample	Weathering Rate
White Mountain National Forest, USA	Hardwood/mixed forest; mean annual precipitation of 1575 mm and mean annual temperature of 5°C. Soils are strong to moderately acidic (3.1-5.3 pH)	Moose (<i>Alces alces</i>) carcasses accumulated from vehicle-collisions and deposited in a central location over the past 15+ years.	WS 1 was observed five months after death of a freshly dumped moose. Of the total sample, most bones showed WS 1 and the most advanced weathering stage observed was WS 3.
Holliston, MA, USA	Hardwood/mixed forest; mean annual precipitation of 1200 mm and mean annual temperature of 9.4°C. Soils are moderately acidic (3.2-5.6pH).	Eighty-seven white-tailed deer (<i>Odocoileus virginianus</i>) remains deposited throughout three microhabitats (grassland, wetland margin, and mixed forest)	WS 1 was first observed five months after deposition in the forested microhabitat and 6 months after deposition in the grassland and wetland margin.
Yellowstone National Park, USA (Miller 2009)	Boreal/mixed forest; mean annual precipitation of 387 mm, mean annual temperature of 4.6°C, dense vegetation, and deep snow pack for at least half the year.	Local large-mammal (ungulate) death assemblages	WS 0: 0-1 years WS 1: 0.3-6.5 years WS 2: 2-10 years WS 3: 3-20+ years WS 4: 6.5-200+ years WS 5: 35-200+ years
Amboseli Park, Kenya (Behrensmeyer 1978)	Savanna; semi-arid with a mean annual rainfall of 350 mm and a mean annual temperature of 26°-34°C, minimal vegetation coverage and alkaline soils.	Multiple large species	WS 0: 0-1 years WS 1: 0-3 years WS 2: 2-6 years WS 3: 4-15+ years WS 4: 6-15+ years WS 5: 6-15+ years
Parc National des Virunga, Zaire (Tappen 1992, 1994, 1995)	Savanna; mean annual rainfall of 930 mm, medium and tall grass, and neutral soil pH.	Single buffalo (<i>Syncerus caffer</i>) skeleton found recently dead	WS 1 was reached two years after death and WS 2 was reached four years after death.
Ituri Rain Forest, Zaire (Tappen 1994)	Tropical rainforest; mean annual rainfall of 1900 mm, mean annual temperature of 31°C, dense vegetation and acidic soils.	Eight elephant (<i>Loxodonta africana</i>) skeletons	WS 0 was seen up to 16 years after death at one site, and the most advanced weathering stage observed (WS 3) was noted after 15+ years at another site.
Nebraska, USA (Fiorillo 1989)	Temperate grassland; open and unshaded field	Adult cattle (<i>Bos Taurus</i>) and juvenile pig (<i>Sus scrofa</i>) selected from domestic carcasses that had died of natural causes at known times.	WS 0: 0.2 years WS 1: 1-3 years WS 2: 3-5 years WS 3: 5-8 years WS 4: 7-8 years WS 5: 7-8 years

Disarticulated extremities were located as far as 48 meters from the initial dump location, while ribs and vertebrae remained near the original location. The epiphyses of long bones were commonly gnawed off, along with the olecranon process of ulnae. This pattern of gnaw marks was also noted on the white-tailed deer remains at the Holliston ORF. However, the frequency of different types of tooth marks varied between the two locations. Scores were more commonly observed in the WMNF than in the microhabitats in Holliston ORF (Table 4.5). This is likely due to the lack of soft tissue on the elements deposited in Holliston ORF. Video footage in the WMNF reveals more tearing of the soft tissue from the skeleton, while video footage in Holliston shows more gnawing.

The types of scavengers also varied between the WMNF and the microhabitats within the Holliston ORF (Table 5.2). However, coyote scavenging was the most prevalent and seen throughout all sites. Black bear, turkey vulture, and raven scavenging were limited to the WMNF, while opossum, fisher, raccoon, great-horned owl, and fox scavenging were only observed at the Holliston ORF. This will likely influence dispersal patterns and the time it takes for whole-carcasses/human remains to be completely consumed and/or scattered. For example, when black bears were observed as part of the scavenging process in the WMNF, whole-moose carcasses were completely consumed/scattered in less than half the time it took when black bears were not involved (Table 4.3). Black bears are rare in the Holliston area, if present at all; therefore consumption and scattering of remains may be expected to occur slower. However, the rate of consumption and disarticulation of remains will vary based on the time of year, number of scavengers feeding, and availability of other food sources.

Table 5.2. Differences in species scavenging in the WMNF and microhabitats within the Holliston ORF.

Location	Scavengers Observed
WMNF	Black bear, coyote, turkey vulture, and raven
ORF Grassland	Great-horned owl and coyote
ORF Wetland	Coyote, fisher, and raccoon
ORF Forest	Coyote, fisher, raccoon, opossum, fox, and squirrel

Within the Holliston ORF, carnivore scavenging was most prevalent in the forested site as depicted by the amount of gnaw marks on the bones and the duration of scavenging observed using the motion-sensitive cameras (Figure 4.11 and Tables 4.4 and 4.6). This may be attributed to thicker vegetation covering the bones in the other sites and eventual water submersion in the wetland margin site. While scavenging halted in the grassland and wetland site during late Summer, scavenging by opossum continued throughout the study in the forested site. Furthermore, while fox squirrels were not initially interested in the bones, one squirrel was observed briefly gnawing on the epiphysis of a long bone six months after deposition (about the same time weathering was first observed). Gnaw mark patterns were similar to those observed in the WMNF, with the epiphyses of long bones typically showing carnivore tooth marks and damage.

Other Taphonomic Alterations on Exposed Remains

The presence of algae and other color staining can be broadly indicative of PMI and depositional location. In both the WMNF and Holliston ORF, algae growth was more prominently associated with the skeletal elements located adjacent to a water

source, though was seen throughout the sites. The rate at which algae was first observed was much quicker in the WMNF than at Holliston ORF. In the WMNF, algae were first noted on the skeletal remains four weeks after deposition of the moose in May but did not occur until 16 weeks after deposition in the wetland microhabitat at Holliston ORF. This difference was even greater for the grassland microhabitat, in which algae was not observed until 34 weeks after deposition. Algae was never observed in the forested site. Moss growth on skeletal remains was observed throughout the WMNF site but had not occurred on any of the bones in Holliston ORF.

Color staining of skeletal elements also revealed significant differences between microhabitats (Figure 4.10) and was most noticeable about eight weeks after deposition. Patchy, dark brown soil staining (Figure 5.3) was noted in all three microhabitats, while dark reddish-gray to white discoloration due to the decomposition was mostly observed in the grassland and wetland sites. As the study progressed, the skeletal elements in the grassland and wetland margin continued to display the highest amounts of bone discoloration, resulting from soil, algae, and decomposition. Conversely, the skeletal elements in the forested site only continued to show signs of soil staining. Staining from decomposition was not noted in the WMNF either. The minimum timing of these processes is summarized in Figure 5.4. Bleaching was first observed in the forest and grassland sites three months after deposition, although cracking was not initiated until five and six months after deposition, respectively. Bleaching was observed in the wetland margin after four months, and cracking was first initiated after six months. Thus,



Figure 5.3. Example of soil staining observed in the wetland margin. Scale is in cm.

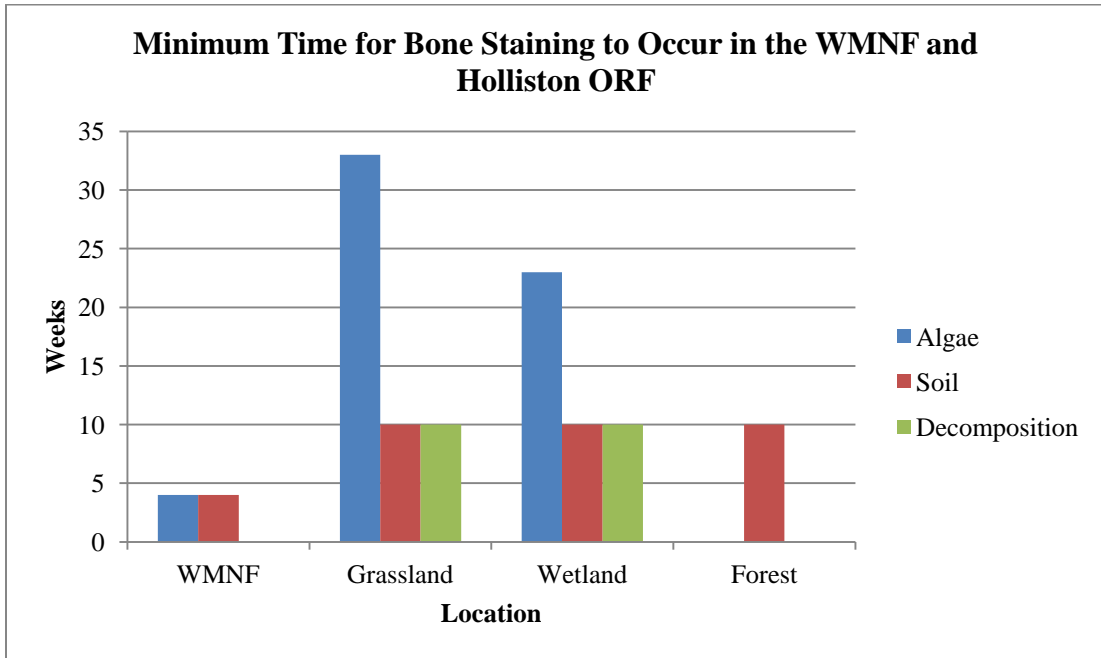


Figure 5.4. The minimum time for algae, soil, and decomposition staining to be observed in the WMNF and microhabitats of Holliston ORF.

the presence or absence of color staining may aid in determining if human or animal remains have been moved from the original location and may broadly indicate PMI.

American carrion beetles were observed in all microhabitats in the Holliston ORF and were most active during the late Spring/early Summer when soft tissue still remained on the bones. Beetles were not observed among the fresh moose-carcasses dumped in the WMNF. A warm, humid climate appeared to be conducive to the presence of American Carrion beetles. This first occurred about two months after deposition of the bones and persisted for approximately six weeks. Thus the presence of beetles may be used to help assess PMI in forensic cases.

Evaluation of the Hypotheses Tested

As mentioned in Chapter 1, the hypotheses this research tested were that the rate of weathering will vary between different regions when compared to previous studies and is dependent on seasonality and microhabitat. The factors expected to influence weathering included sun exposure and freeze/thaw cycles. This research reveals that the onset of weathering is similar to other New England taphonomic studies (Sorg 2012) and is also comparable to the initial rates described for Amboseli Park, Kenya (Behrensmeier 1978), Yellowstone National Park, USA (Miller 2009), Nebraska, USA (Fiorillo 1989), and Parc National des Virunga, Zaire (Tappen 1992, 1994). However, these rates are significantly different when compared to that of rainforest environments (Pokines 2009; Tappen 1994).

As expected, sun exposure and freeze/thaw cycles appeared to influence the rate of weathering. The most significant weathering changes observed in the WMNF occurred just after snowmelt in the area. The increased weathering is likely a result of temperature fluctuations just prior to and immediately following consistent snow coverage; temperature fluctuations were noted to be greatest during this time. Furthermore, the vegetation was minimal, resulting in increased sun exposure. Similarly, the greatest increase in weathering at the Holliston ORF was observed in October, which also corresponds with a high frequency of temperature fluctuations above and below freezing.

At this time, the microhabitats tested at the Holliston ORF (grassland, wetland margin, and forest) did not reveal a statistically significant difference in the initial rates of weathering ($p = 0.53$). However, weathering cracks were more pronounced in the forested site than in the grassland or wetland margin. This is likely due to more consistent sun exposure in the forested site. A longer duration of study may suggest that microhabitats significantly influence weathering.

CHAPTER 6: CONCLUSIONS

Assessing the PMI remains a crucial factor in resolving forensic cases. Forensic anthropologists are more commonly relied upon at crime scenes to assist in reconstructing a series of events related to taphonomic processes. Methods used to determine the PMI are more accurate during the early stages of decomposition but remain limited in applicability to the later stages. Other methods such as the dating of plant root growth are less frequently applied due to the rarity of adequate botanical recovery found in association with the remains. Additionally, radiocarbon dating is not applicable until prior to AD 1950, and its primary function is to determine if remains are of forensic interest at all. Further research into the rates of bone weathering addresses the lack of viable options available to assess PMI in the more advanced stages and helps to fill the large gap between the loss of soft tissue and radiocarbon dating.

The results of initial rates of osseous weathering presented in this study are similar to other current New England taphonomic studies. The samples in both the WMNF and Holliston ORF revealed WS 1 first to occur five to six months after deposition. Similarly, Sorg (2012) noted WS 1 to occur six months after exposure in a forested environment in Northern New England. These initial results are also comparable to the initial weathering rates described for Amboseli Park, Kenya (Behrensmeyer 1978), Yellowstone National Park, USA (Miller 2009), Nebraska, USA (Fiorillo 1989), and Parc National des Virunga, Zaire (Tappen 1992, 1994). On the other hand, significant differences are noted when compared to Ituri Rain Forest, Zaire (Tappen 1994) (Table 5.1). This is likely due to consistently thick vegetation coverage, high amounts of

precipitation (1900 mm annually), and a more equable environment associated with the rainforest environment. However, a longer duration of study is needed to glean more meaningful data into the later stages of weathering.

A chi-square test revealed that the microhabitats investigated in Holliston ORF were not a statistically significant factor in weathering 50 weeks after deposition ($p=0.53$), although variations were observed in the initial onset and progression of weathering. Skeletal remains deposited in the forested site revealed WS 1 one month prior to the grassland and wetland margin, and the weathering cracks in the forested site were larger and more pronounced (Figure 5.2). Vegetation coverage was minimal in the forest compared to the other microhabitats. Additionally, the elements in the wetland margin became partially or fully submerged in water from late June through the end of the study. A larger sample and longer duration of exposure would likely suggest weathering to be significantly influenced by microhabitat.

The most significant weathering changes observed in the WMNF occurred between December and late April, in which ten elements had progressed from WS 1 to WS 2. The total number of days in which the site experienced temperature fluctuations above and below freezing was 81, mostly which occurred in December, March, and April. However, snowpack in the area was at least 30 cm mid-January through mid-March. Advancement of weathering corresponded with the months in which temperature fluctuations were greatest. This occurred just prior to and following consistent snow coverage. Therefore, moisture and temperature fluctuation occurring prior to and after snowfall is likely a strong factor in the advancement of osseous weathering.

Other taphonomic factors that were commonly observed in conjunction with weathering included carnivore scavenging and tooth marks, algae growth, and other color staining, all of which can mask the presence of and influence the rate of weathering. Dispersal of extremities was commonly observed to occur up to 45 meters in the WMNF, and many skeletal elements from freshly dumped moose could not be located based on a 100 m search radius. The type of scavengers varied greatly between sites and within the Holliston ORF (Table 5.2). Black bear, raven, and turkey vulture scavenging were limited to the WMNF, while fisher, raccoon, and opossum were only observed in Holliston. Coyotes were observed the most often and throughout all sites. In the WMNF, whole moose carcasses were completely consumed and scattered in as little as nine days. Human remains deposited in a similar forested environment may be expected to be consumed much quicker and scattered further distances based on obvious size differences. In a forensic context, understanding dispersal patterns and transport by scavengers can aid in the recovery of human remains (Haglund 1997; Haglund *et al.* 1989).

The presence of algae and various color staining can also be broadly indicative of PMI and disposal locations. Algae was more prominently observed on skeletal elements adjacent to a water source, though was observed throughout the WMNF site and in both the wetland and grassland microhabitats. Algae formation was never observed in the forested microhabitat. The rate at which algae occurred was much quicker in the WMNF (27 days after deposition) than in the wetland margin (16 weeks after deposition) and grassland site (34 weeks after deposition) (Figure 5.4). Brown soil staining was present

throughout all sites and also occurred quicker in the WMNF (27 days after deposition). These taphonomic processes are also widely influenced by the environment in which the remains are deposited and must be considered when applying it to forensic cases.

The rate of osseous weathering remains highly variable and is largely a factor of climates (i.e., temperate deciduous forest, semi-arid equatorial savanna, or tundra) and various microhabitats within that climate (i.e., patches of forest, brush, wetland, or grass cover within a temperate deciduous forest) (Table 5.1). Generally, skeletal remains deposited in a cooler, temperate climate experience longer durations of survival (Andrews and Armour-Chelu 1998; Andrews and Cook 1985; Fiorillo 1995; Miller 2009) than skeletal remains deposited in a semi-arid savannah climate (Behrensmeyer 1978; Coe 1978; Isaac 1967; Tappen 1994). However, continued taphonomic research is needed throughout different regions to more accurately assess PMI. Weathering can be applied critically when considering all environmental factors to establish PMI when soft tissue decomposition has completed and radiocarbon dating is not practical. Other taphonomic factors also remain largely influenced by climate and microhabitat and need to be studied regionally. Expanding the taphonomic literature can aid in understanding the patterns and rates of these processes and ultimately assist in resolving forensic cases.

This study serves as the first part of continued research into the investigation of weathering rates in New England. Continued documentation of bone weathering progression at Holliston ORF will eventually provide additional information on the effects of microhabitat, at which time, the statistical significance of microhabitat on weathering can be reevaluated. Continued observations in the WMNF will also provide

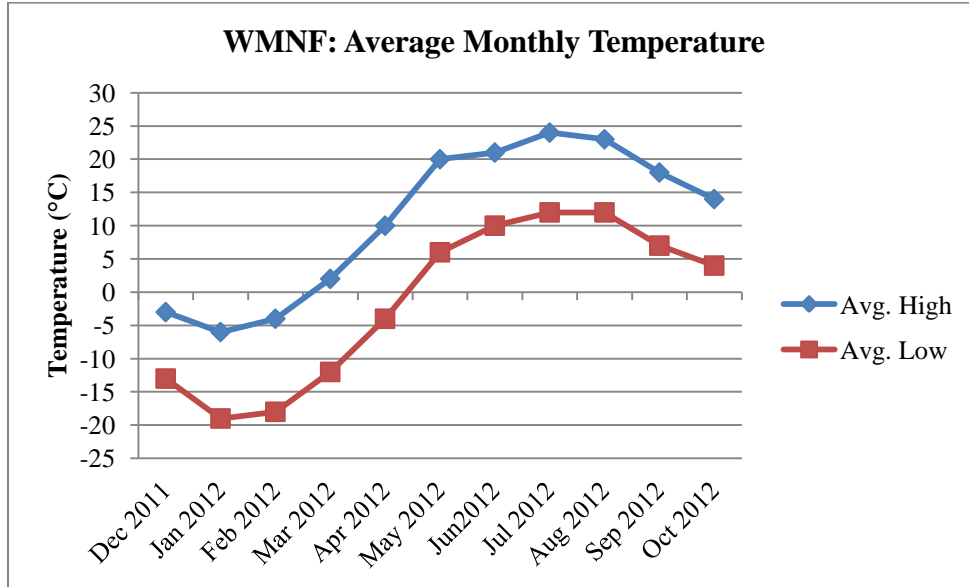
more meaningful data for northern New England and for regional, comparative analyses of advanced weathering stages.

Other anthropological research facilities throughout the U.S. also can provide opportunities for future taphonomic studies. The diverse locations of these facilities can yield data on the influence of various regions and microhabitats. Numerous taphonomic studies have emerged out of the Anthropology Research Facility in Knoxville, TN (Bass 1997; Mann *et al.* 1990; Rodriguez and Bass 1983, 1985; Schoenly *et al.* 2005, 2007; Vass *et al.* 1992, 2008). This facility was established in 1980 and is able to use donated human cadavers to carryout research. Located in the southeastern part of the U.S., the research from this facility represents taphonomic changes associated with a hot, humid climate. The Forensic Anthropology Research Facility located at Texas State University in San Marcos also supports the use of human cadavers for outside decomposition studies (Sears and Spradley 2013). This facility is located in central Texas and represents a semiarid region with cool winters and hot summers. More recently, the Department of Anthropology at Southern Illinois University Carbondale developed a research facility for the use of taphonomic studies. This facility, known as the Complex for Forensic Anthropology Research, currently uses pig cadavers for decomposition and scavenger studies specific to the Midwest (Martin and Dabbs 2012). In west-central Colorado, Colorado Mesa University established a new facility in 2012 known as the Forensic Investigation Research Station. Domestic pigs are currently being used for decomposition studies as a human donation program is initializing (Connor 2013). This

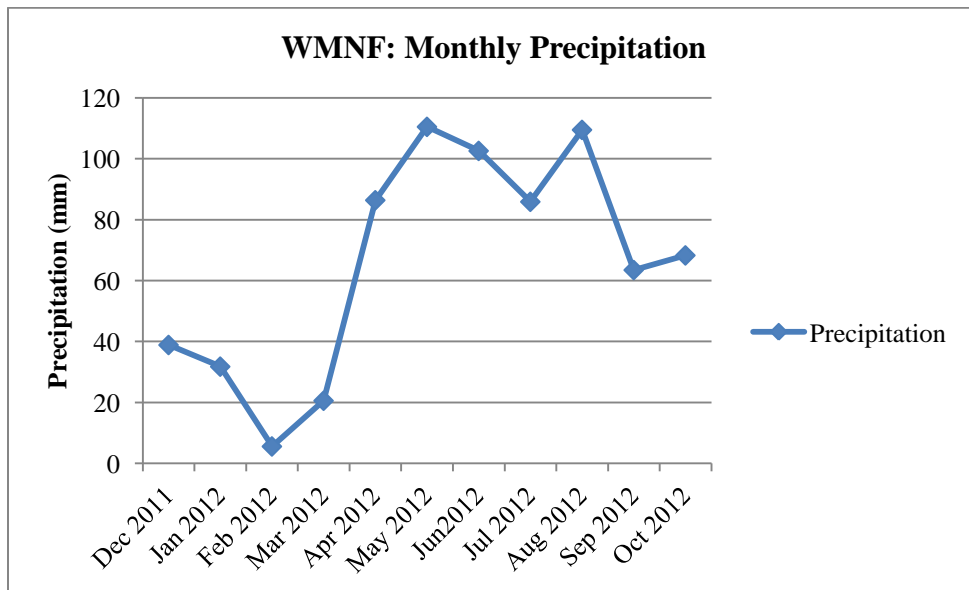
new facility can be used to investigate taphonomic changes in an arid, high-altitude climate.

Although these facilities are working to expand the taphonomic literature, bone weathering data still remains limited. This is likely due to the longer duration of study needed to acquire more meaningful results. However, these facilities serve as a resource for future bone weathering studies and have great potential to shed light on the climatic and microhabitat factors influencing variations in taphonomy. The Holliston ORF, in collaboration with other anthropological research facilities, provides endless opportunities to carryout taphonomic studies. The projects conducted throughout these locations will aid in determining regional variations and will therefore assist in assessing a more accurate PMI to resolve forensic investigations.

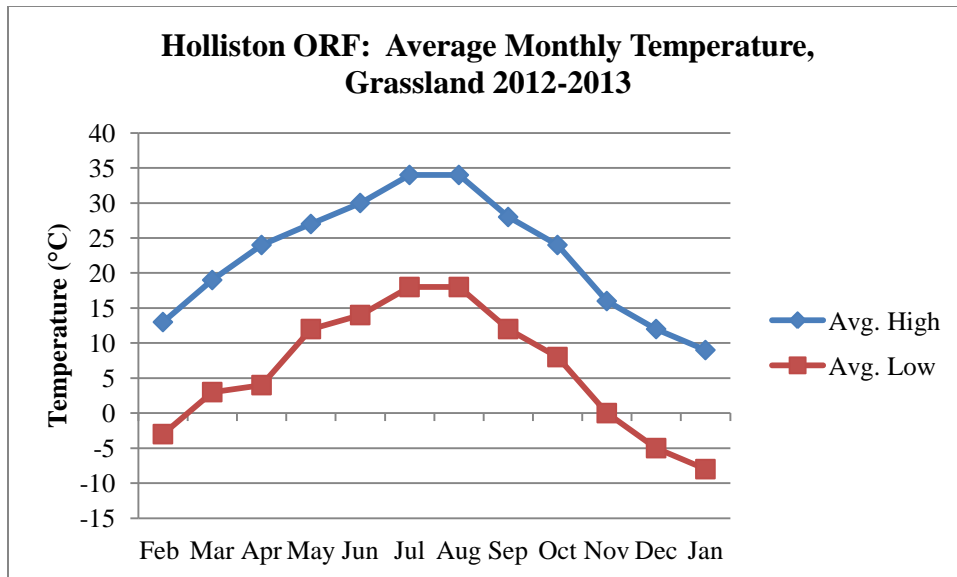
APPENDIX A: WEATHER DATA



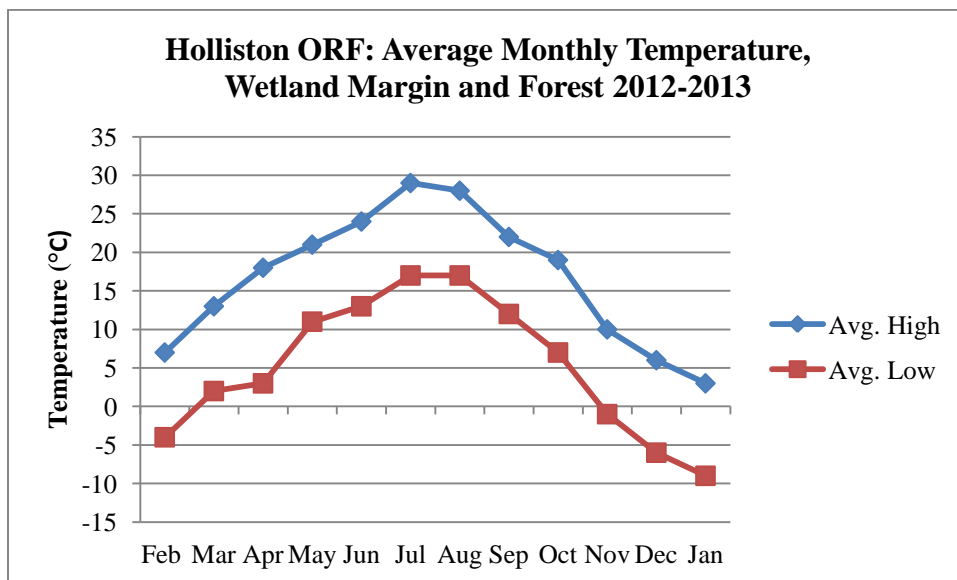
A.1. Average monthly temperatures for the WMNF site location.



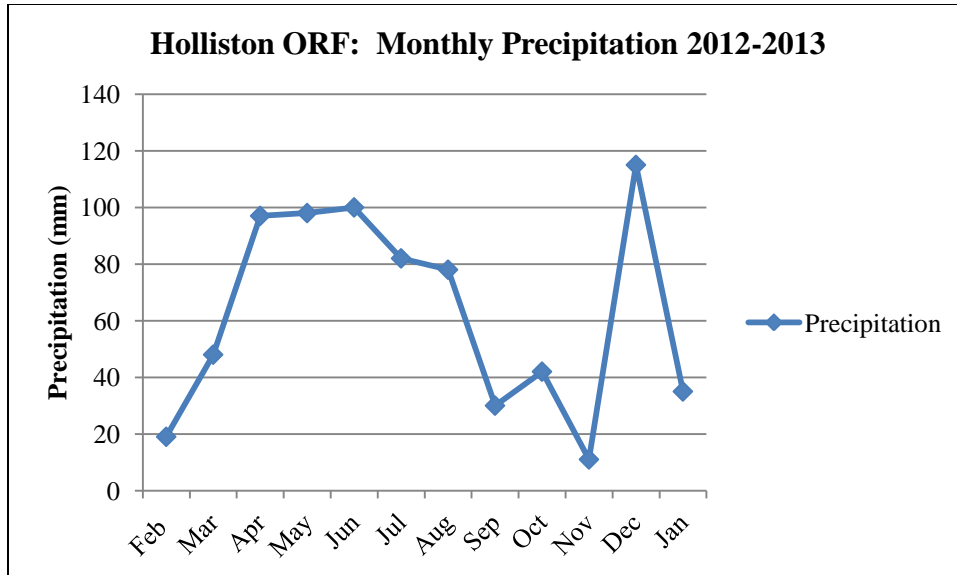
A.2. Average Monthly Precipitation for the WMNF site location.



A.3. Average Monthly Temperature for the Grassland microhabitat at Holliston ORF. Note the difference in temperate compared to the wetland margin and forest microhabitats (below). The average monthly high for the grassland microhabitat was consistently 6° C warmer.



A.4. Average monthly temperatures for the wetland margin and forest microhabitats. These two microhabitats were consistent in temperature, while the grassland varied from these.



A.5. Average monthly precipitation in mm for Holliston ORF.

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