University of Alberta

Bone Weathering in a Cold Climate:

Forensic Applications of a Field Experiment using Animal Models

By

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Abstract

This study systematically observed weathering rates in a cold climate in order to develop standards for the determination of the postmortem interval in forensic contexts. To determine which species are suitable analogues for the human skeleton, the cortical density and geometry of deer and pig long bones were compared to those of humans. The bones of deer and humans were found to be similar in terms of their cortical properties and weathering patterns. The results of the field experiment showed that bleaching and cracking caused by weathering in a cold climate are delayed compared to arid climates but occur more rapidly than in temperate environments. Weathering stages were developed for different skeletal elements and variations in different microenvironments were noted. This research adds to the limited body of knowledge on weathering in a cold climate and will increase the precision with which weathering stages can be used to assign time-since-death.

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1. Introduction and Background

1.1 Introduction

Taphonomy is the area of study that describes and systematizes the processes that alter remains after death (Gifford, 1981). Initially developed within palaeontology, and later applied to archaeology and palaeoanthropology, taphonomy is increasingly being studied in forensic anthropology, with a focus on the more recent postmortem interval. Forensic taphonomy involves the collection and analysis of data concerning the depositional context of human remains (Haglund and Sorg, 1997). Taphonomic information can be applied in a forensic context to the determination of the postmortem interval, the reconstruction of postmortem events, the recovery of remains and evidence, and the distinction of human behaviour from taphonomic processes (Haglund and Sorg, 1997). Forensic cases have much shorter postdepositional histories than archaeological or palaeontological assemblages, thus a greater number of modern analogues are available and there is greater potential for complex reconstruction (Gifford, 1981). Experiments in forensic taphonomy involve the observation of contemporary taphonomic processes and focus on identifying patterns that are comparable to those observed in recent human remains.

Bone weathering is a taphonomic process on which little research has been conducted by forensic anthropologists. Behrensmeyer (1978) defines weathering as the process by which organic and inorganic components of bone are separated and destroyed by physical and chemical agents. Bone weathering involves the eventual disintegration of skeletal elements caused by exposure to sunlight as well as fluctuations in temperature

and moisture (Miller, 1975; Shipman, 1981; Ubelaker, 1997). Although bone weathering rates and patterns reflect local conditions, the sequence of changes is relatively stable and provides a standardized way of assessing weathering, which is important in interpreting the depositional environment (Buikstra and Ubelaker, 1994).

One of the most challenging determinations facing forensic anthropologists is that of the postmortem interval, since, as time-since-death increases, the accuracy with which it can be estimated decreases (Schoenly et al., 1991). Other than determinations based on entomology, estimates of the postmortem interval for both human and animal remains are largely subjective (Cox et al., 1994). Bone weathering is one of the few indicators of time-since-death available in cases of skeletonized human remains, and some forensic anthropologists have applied bone weathering stages that were never meant for use in forensic contexts (Buchan and Anderson, 2001). Behrensmeyer (1978) developed a series of weathering stages based on the observation of mammal bones in Africa and correlated these with known times of death. The purpose of these categories was to provide a basis for the investigation of weathering processes, the comparison of bones from different contexts, and the correlation of stages with time-since-death (Behrensmeyer, 1978). Different weathering stages are defined by the presence and severity of cracking, flaking, and bleaching of exposed skeletal elements (Behrensmeyer, 1978; Shipman, 1981). Although the extent of weathering is directly related to the time of exposure of the skeleton, several factors cause variation in weathering patterns and rates, making the determination of standard weathering stages problematic.

This study represents the first taphonomic field experiment to systematically observe weathering rates in cold climates in order to develop standards for their

application to establishing time-since-death in forensic contexts. The present research also investigates whether pig and deer skeletons are suitable models for human remains in taphonomic experiments by comparing the size, density, and cortical properties of the long bones of each species.

1.2 Background

1.2.1 Bone Weathering

Weathering is one of the most destructive taphonomic processes acting on skeletal remains (Phoca-Cosmetatou, 2002) and can be identified by several distinctive alterations made to skeletal elements. Weathering causes microfissures and cracks to form parallel to the alignment of collagen fibers, and these fissures deepen over time, exposing more bone surface area to the elements and encouraging further disintegration and decomposition (Tappen and Peske, 1970; Behrensmeyer, 1978; Shipman, 1981; Grupe and Dreses-Werringloer, 1993). Cracks can develop quite rapidly in hot, arid climates (Shipman, 1981). Hide, ligaments, cartilage, and periosteum become desiccated and eventually disintegrate completely (Miller, 1975; Behrensmeyer, 1978). Exposure causes the thin outer layers of bone to flake, usually beginning along the margins of cracks (Behrensmeyer, 1978). Once the external layer has flaked away, the fibrous texture of the exposed bone surface can be seen. Surfaces become bleached and chalky when exposed to sunlight (Brain, 1967; Miller, 1975; Galloway et al., 1989; Andrews, 1995). Prolonged exposure to ultraviolet light degrades the organic component of the bone and eventually results in calcination (Ubelaker, 1991). In the more advanced stages of weathering, cracks penetrate the bone cavity and splinters are loosened, causing the bone to fall apart

(Behrensmeyer, 1978). Although it is widely agreed that bone weathering results from exposure to moisture and sunlight, other researchers define weathering more broadly.

Ubelaker (1997) defines weathering as the response of bone to its immediate environment, including aspects such as soil, and Behrensmeyer (1978) includes both physical and chemical processes as factors in weathering. Chemical bone destruction depends in part on soil pH and drainage, which affect the hydrolysis of the mineral component of bone (Grupe and Dreses-Werringloer, 1993). Bone destruction caused by biological agents includes root etching but is mainly due to the action of fungi and bacteria (Grupe and Dreses-Werringloer, 1993; Phoca-Cosmetatou, 2002). Microorganisms cause destructive focal lesions and enhance the disintegration of bone by producing acidic metabolites and proteolytic enzymes that act on both the collagen component and mineral matrix of bone (Grupe and Dreses-Werringloer, 1993; Bell et al., 1996). Microorganisms in the soil are known to cause tunneling in compact bone, and endogenous microflora found in the digestive tract may also contribute microstructural damage during decomposition (Bell et al., 1996). If this is the case, then initial bone degradation may begin very soon after death and well before skeletonization (Bell et al., 1996).

Variables Affecting Bone Weathering

Variables affecting weathering processes include intrinsic factors such as animal species, age, and size, as well as skeletal element composition, density, and surface area. External conditions such as initial decomposition and scavenger activity, as well as climate and micro-environment also influence weathering rates. These sources of

variability present difficulties when applying a single set of weathering stages, developed in a specific setting, to diverse depositional contexts.

Behrensmeyer (1978) created descriptive categories of weathering based on the systematic observation of bones of recently deceased medium to large mammals in Kenya. Her weathering stages consist of easily observable criteria and straightforward descriptions that can be readily learned and recognized (see Table 1.1). Categorization is sometimes problematic, however, since the weathering stages are arbitrary divisions of a continuous process. In order to compensate for this, only the most advanced stage evident on the bone surface is recorded.

Although Behrensmeyer's weathering stages have been used for more than twenty-five years, some concerns regarding their application have surfaced. Certain bones show weathering patterns that do not fit into any of the six stages, such as skeletal elements that exhibit flaking without extensive cracking or display "mosaic" cracking of articular surfaces (Behrensmeyer, 1978). Teeth have not been consistently associated with bone weathering stages, due to variation in eruption patterns, enamel to dentin ratios, and overall morphology of different teeth. Factors such as soil composition, microbial or insect activity, and root etching can cause atypical patterns of weathering. Behrensmeyer (1978) attempts to control for variability by using the most severely weathered skeletal elements of a carcass to determine its degree of weathering. However, bones in advanced stages of weathering may be preferentially removed and gnawed by ungulates and rodents, causing the weathering stage of a skeleton to be underestimated (Lyman and Fox, 1997). Long bone shafts may be easiest to categorize into weathering stages, however, limbs are often carried away by scavengers.

Table 1.1. Behrensmeyer's Weathering Stages and Associated Years-Since-Death

STAGE	DESCRIPTION	YEARS SINCE DEATH
0	Bones surface shows no sign of cracking or flaking. Usually bone is still greasy, marrow cavities contain tissue, skin, fat, and muscle/ligament may cover part or all of the bone surface.	0-1
1	Bone shows cracking, normally parallel to the fibre structure. Articular surfaces may show mosaic cracking of covering tissue and the bone itself. Soft tissue may be present.	0-3
2	Outermost concentric thin layers of bone show flaking, usually associated with cracks; 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 this stage. Deeper and more extensive flaking follows, until most of the outermost bone is gone. Crack edges are usually angular in cross-section. Remnants of soft tissue and cartilage may be present.	2-6
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 1-1.5mm at this stage, and bone fibres are still firmly attached to each other. Crack edges usually are rounded in cross-section. Soft tissue rarely present at this stage.	4-15+
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.	6-15+
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 bones.	6-15+

Modified from Behrensmeyer (1978:151 & 157, Table 2)

In the past, Behrensmeyer's (1978) stages have been applied without consideration of the many factors influencing weathering rates. Although the basic composition of mammal bone is fairly constant, different bones vary greatly in the arrangement and distribution of their organic and inorganic components, causing bones to have differing levels of resistance to attritional forces (Singh et al., 1974; Gifford, 1981). Tappen and Peske (1970) found that weathering cracks tend to follow the orientation of the majority of collagen fibers of the compact bone matrix in that area. The effects of repeated fluctuations in temperature and moisture may be affected by a bone's thickness and density (Behrensmeyer, 1978). Different skeletal elements exposed at the same time commonly exhibit varying weathering stages; for instance, small compact bones weather more slowly than other skeletal elements and do not exhibit all the typical features of the established weathering stages (Behrensmeyer, 1978; Shipman, 1981). Gifford (1981) states that, for most land mammals, bones such as vertebrae, ribs, scapulae, sacra, and innominates tend to be more susceptible to damage, and that bones with a high ratio of surface area to volume disintegrate faster than those with lower ratios when subjected to weathering processes. Because of the significant structural variation among different skeletal elements, several different bones should be assessed when assigning a weathering stage to a skeleton (Behrensmeyer, 1978). Long bone shafts as well as flat bone surfaces are recommended for assessing the extent of weathering rather than edges or damaged parts of bones. Unfortunately, little research has been conducted on the way in which specific skeletal elements weather (see Todd et al., 1987 for an exception), and detailed information on the *relative rates* at which different bones weather is not available (Lyman and Fox, 1997).

Variation in the structural features of bones among different species also affects weathering rates. Due to anatomical differences, the bones of mammals of similar sizes from different taxa have been observed to weather at different rates (Hill 1975; Gifford, 1981). According to Miller (1975), the size of an animal does not seem to affect pattern of weathering cracks over the long term, however, research carried out by Behrensmeyer (1978) has shown that mammals weighing less than five kilograms appear to have different weathering characteristics than larger species, showing more cracking and splintering rather than flaking. The bones of mammals weighing less than one hundred kilograms tend to weather more quickly than those of larger animals, and the bones of both small adults and juveniles of larger species are preferentially destroyed. Juveniles are underrepresented in the later weathering stages compared to small adult animals, indicating that immature bone structure may be a more significant factor than size in weathering rates (Behrensmeyer, 1978). Fetal and very young bone found associated with the mother's skeleton are usually more weathered by one or two stages. Hill notes that unfused portions of juvenile bones are exposed to further damage as they become disarticulated (1975).

Even minor variations in micro-environment can affect weathering patterns. Field observations have shown that different parts of the same bone can weather at different rates (Behrensmeyer, 1978; Gifford, 1981). The upper, exposed surface of a bone is often more weathered than the surface in contact with the ground, although parts of bones that project more than ten centimeters above the ground often weather more slowly than those near the surface (Behrensmeyer, 1978). The moisture content, temperature, and nature of the soil surface are important factors in bone weathering (Lyman and Fox, 1997). The

subaerial zone in open micro-environments is subject to wide diurnal fluctuations in temperature and humidity, and the intensity and duration of these fluctuations affect weathering processes (Behrensmeyer, 1978). In general, bones weather less quickly in more stable micro-climates, such as those created by vegetation cover (Hill 1975; Behrensmeyer, 1978). Gifford (1981) found that, within a single skeleton, weathering rates can vary due to the location of bones in different micro-environments, such as well-drained versus periodically flooded areas or shaded versus sun-exposed areas. Although different micro-environments seem to have an effect on weathering patterns, the amount of variation required to significantly alter weathering rates is not known, and the spatial scale at which micro-environmental variation affects weathering rates is not clear (Lyman and Fox, 1997).

Localized conditions such as vegetation, shade, and moisture may be more important factors than general habitat in their effects on weathering processes (Behrensmeyer, 1978). Behrensmeyer (1978) made observations of bones in six different habitats: swamp, dense woodland, open woodland, plains, bush, and lakebed, although she states that the samples observed in each habitat were quite small and this may have obscured differences in weathering patterns. In general, weathering appears to be slower in the swamp and dense woodland habitats, where moisture and shade provided by vegetation tend to moderate the diurnal and seasonal fluctuations in temperature and humidity near the soil surface (Behrensmeyer, 1978; Haynes, 1981; Tappen, 1994). However, growing plant roots can widen cracks in bone, and acids secreted by the roots facilitate bone decomposition (Behrensmeyer, 1978; Haynes, 1981).

Although the structural features of bones have a strong influence on general weathering characteristics regardless of climate, relatively little is known about how bones weather under different conditions (Behrensmeyer, 1975). Behrensmeyer (1978) concludes that further sampling over a broad range of environments is necessary and that the effects on weathering rates of freeze-thaw cycles in temperate climates need to be tested. Gifford (1981) observes that research in the North American Plains may indicate that bones weather more swiftly in other areas, and that it should be possible to calibrate rates of bone weathering for other types of environments. Tappen (1994) observed very different weathering patterns in a savanna environment compared to those seen in the rain forest, where weathering is greatly delayed.

Behrensmeyer (1978) notes that the effects of the initial conditions of decomposition on subsequent weathering are unknown. Factors such as cause of death, manner of exposure, and consumption by scavengers can affect weathering stage assignment (Lyman and Fox, 1997). Endogenous microorganisms in the digestive tract may contribute to the degradation of bone structure, spreading through cortical bone via the Haversian blood supply during decomposition; therefore, scavengers feeding on the viscera could alter the initial postmortem change to skeletal microstructure (Bell et al., 1996). Bones are exposed to weathering agents after soft tissues detach from the bones, thus, the time of exposure depends on the way in which hide, muscle, and other tissues decompose or are removed by scavengers (Hill, 1979; Micozzi, 1986; Lyman and Fox, 1997). Under certain conditions, hide and ligaments may keep skeletal elements in articulation and can endure for a relatively long time where there is little remaining flesh (Toots, 1965; Behrensmeyer, 1975). Hill (1979) proposes that the bones which are last to

disarticulate, such as vertebrae, may have a greater resistance to destructive taphonomic processes, since articulating surfaces are protected and soft tissue is retained. Toots (1965) observes that weathering, splintering, and disintegration of other skeletal elements normally begins before the vertebral column is even completely disarticulated. By recording only the most advanced weathering stage apparent on the skeleton, Behrensmeyer controls for factors which might slow weathering rates or shorten exposure duration for each carcass (Lyman and Fox, 1997). When correlating weathering stages to the postmortem interval, Behrensmeyer assumed that the maximally weathered bone of a carcass was exposed immediately after death, however, exposure duration is invariably less than time-since-death (Lyman and Fox, 1997).

Previous Weathering Studies

Behrensmeyer (1978) found that weathering stages could be used to estimate the minimum number of years since death. In the semi-arid climate of Kenya, longitudinal cracks often appeared on long bones within a few days of exposure. In Kenya, bones displayed flaking, splitting, and splintering during the first few months of exposure on the soil surface and most bones completely disintegrated in less than fifteen years (see Table 1.1). Behrensmeyer (1978) suggests that more carcasses with known times of death need to be observed over several years before it is possible to accurately assign the most probable number of years of exposure to bones at a given weathering stage. Lyman and Fox (1997) suggest that if Behrensmeyer's original control sample of fifty-two carcasses were significantly enlarged, the correlation of weathering stage with time-since-death would decrease considerably due to variation within and between carcasses. Behrensmeyer (1978) maintains that her hypotheses about weathering processes need

further testing and that the stages presented are "provisional" descriptive categories that may need elaboration and revision as additional research is conducted. Although many studies on bone weathering have been undertaken since this research, all have used the weathering categories created by Behrensmeyer, and very little elaboration or revision has taken place.

Miller (1975) observed the remains of cattle and horses in a mountainous desert region of California, with an average temperature range of 0 to 49°C. Following death, the periosteum protected bones from desiccation; the gnawing of bones by carnivores and rodents removed this outer layer. Small cracks sometimes appeared even before the periosteum was completely removed (see Table 1.2). After one year, longitudinal cracks extended into the marrow cavity, and exposed patches of bone were bleached to a brilliant white. Surface exfoliation normally started after four years. Scavengers removed soft tissue and expose bones to weathering processes more quickly; bones that were fed upon by scavengers were more likely to have most of their periosteum removed and were thoroughly bleached with many longitudinal cracks (Miller, 1975).

Gifford (1984) monitored ungulate carcasses exposed in a semi-desert climate in Africa using the stages developed by Behrensmeyer. It was observed that vertebrae survived more frequently than other skeletal elements, while podials and phalanges were less commonly recovered, possibly due to their burial or consumption by carnivores. Most bones were at weathering Stage 1 within six months of exposure. After ten years, it was found that most of the equid bones had weakened structures, while the few bovid bones that were recovered were disintegrating, although the teeth were still quite well

preserved. Not surprisingly, Gifford's (1984) findings on weathering rates corresponded with those studied by Behrensmeyer in a similar climate.

Table 1.2. Miller's Bone Weathering Progression and Time-Since-Death

DESCRIPTION	YEARS SINCE
Loss of < 5% of the periosteum, not more than one small longitudinal crack per bone	< 1
Approximately 25% of the periosteum gone, exposed bone thoroughly bleached, 2-3 longitudinal cracks present, penetrating	1-2
Transverse cracks appear	2-4
Periosteum completely absent, many longitudinal and transverse cracks present, exfoliation just beginning, surface becoming	4-18
Most of the organic component gone, bones are a dull, greyish color, exfoliation has increased rapidly	18-30
Bones severely deteriorated with many splinters	> 30

Based on Miller (1975: 217-218)

Brain (1967) set up experiments in southwest Africa to distinguish between the effects of arid and more humid environments on bones. Some bones were placed in areas fully exposed to the sun, others were kept in open, shaded areas, and some were buried under leaves. The bones collected on the desert surface had bleached, chalky surfaces after several years and often had adhering remnants of desiccated tissue. In the more humid micro-environment, bones lying in a well-drained area showed similar characteristics. In contrast, Tappen (1994) conducted a study in Africa using drastically different habitats and found clear variation in weathering patterns. Tappen (1994) found that the pattern of bone weathering in the savanna environment of Zaire is similar to that

observed by Behrensmeyer; however, in the rain forest, cracking caused by weathering was delayed or absent and bones did not become bleached by the sun. Dense vegetation provided a micro-environment in which there was little daily variation in temperature and humidity. The slower rates of weathering found in humid habitats indicate that drying plays an important role in the cracking of bone.

In a weathering study conducted in a temperate environment, Andrews (1995) established a long-term taphonomic experiment in the United Kingdom. The bones of sheep, cows, horses, foxes, and other small mammals were left undisturbed in a wide variety of habitats. In wet, sheltered micro-environments, bones were corroded at their articular ends and there was considerable loss of cancellous bone before they reached Behrensmeyer's Stage 1. Bones in areas without vegetation were bleached, but weathered much more slowly than the rates reported by Behrensmeyer, reaching Stage 1 around ten years after death. In contrast, the bones of small mammals were observed to split, decalcify, and collapse within five years of exposure, much more quickly than the large mammals observed by Behrensmeyer.

Bone Weathering in Cold Climates

Fewer studies have been conducted in temperate and cold climates than in hot, arid or humid climates. Haynes (1980) observed the skeletons of large ungulates in Canada and in the north-central United States and found that the sequence of bone deterioration due to weathering appears to be similar to that recorded by Behrensmeyer. Long bones in shaded, moist areas often retained marrow, and long bones that were not gnawed open remained greasy at epiphyseal ends (see Table 1.3). In moist, shaded micro-environments such as wooded areas, moss growth contributed to bone destruction.

Table 1.3. Bone Weathering Progression and Time-Since-Death in a Cold Climate

DESCRIPTION	TIME SINCE DEATH
Bones lying in shaded woods when temperatures are above freezing have nearly all soft tissue removed, bones exposed in meadows or grasslands retain significant soft tissue for months; once soft tissue is removed, bones dry out and begin to crack within a few hours	2-3 months to < 1 year
Bones in shaded, moist areas retain marrow during the spring, summer, and sometimes part of fall	6-9 months
Some vertebrae remain articulated for a year or more, normally become separated after two winters	1-2 years
Bones are generally dry, may still be greasy if epiphyseal ends	2 years
Exfoliation and splintering of bone during periods of dry warmth	---

Based on Haynes (1981)

In open meadows or grasslands, when precipitation was very low, remaining hide became desiccated and resisted consumption or decay, providing protection for the underlying bones. It was observed that bones lacking soft tissue dried out and began to crack within a few hours, and that cracking was accelerated after the marrow was decomposed or consumed. Dry bone retaining some collagen began to exfoliate and splinter when exposed to periods of dry warmth. In the subhumid-subarctic climate of northern Alberta, bones were normally covered with snow for six months and were not exposed to drying and warming or to direct sunlight (Haynes, 1981). Although the sequence of bone deterioration observed in north-central North America may be similar to that in Africa, the length of time it takes for bones to pass through each weathering stage can differ greatly.

Todd and colleagues (1987) observed the animal bones from an archaeological site in Wyoming to determine the degree of weathering displayed by different bones.

They noted that the differences in structure between long bones and compact bones lead to different patterns of surface alteration; therefore, a new set of descriptive categories was developed for assigning weathering stages to compact bones and articular surfaces (see Table 1.4). The authors state that additional experimental research is needed to determine the weathering rates and characteristics of different skeletal elements.

Table 1.4. Todd and Colleagues' Weathering Categories for Compact Bones and Articular Surfaces

STAG	DESCRIPTION
1	Unweathered, articular surfaces intact with no surface cracking
2	Articular surfaces intact with some cracking
3	Articular surfaces exhibit some deterioration, but more than 50% of the surface remains intact
4	Intact articular surfaces restricted to a few small "islands"; less than 50% of articular surfaces remain intact
5	No articular surface area remains intact
6	Bone severely deteriorated; large areas of fibrous bone exposed

Modified from Todd *et al.* (1987:64, Table 3.3)

In the same year, Todd (1987) noted that mammals in the North American Plains that died in fall or winter became frozen and tended to decompose and disarticulate differently than those that died in the summer. He also observed that remains covered with snow showed marked differences from bones in areas not covered by drifts in the extent of their disarticulation, dispersal, and deterioration. Observations of contemporary animal bones in central North America indicated that some skeletal elements took up to fifty years to reach weathering Stage 6; in forested mountain areas, hundred-year-old bison bones were found on the surface at Stages 3-4 (Todd et al., 1987). Despite these North American field studies, the rate of bone weathering in cold climates and the effect of freeze-thaw cycles remain poorly understood.

To confirm the observations of bone weathering made in field experiments and to investigate their cause, Miller (1975) conducted a more controlled, somewhat artificial laboratory study in order to examine the effects of freeze-thaw cycles on bone. It was discovered that cattle tibiae and metapodials that were frozen at -20°C then thawed at temperatures between 10 and 24°C developed cracks parallel to the longitudinal axis within twelve hours, while those that were soaked for three weeks then dried under the same conditions developed cracks only after twenty-four hours.

Weathering of Human Bone

Research on the weathering of human bone has been conducted using past forensic cases with known times of exposure. Galloway and colleagues (1989) conducted a retrospective study of autopsy and forensic anthropological reports from Arizona where, during the winter, temperatures often drop rapidly to near freezing at night. They noted that desiccated tissue often remained at sites of muscle and ligament attachment.

Bleaching and exfoliation of cortical bone, followed by exposure of cancellous bone and fragmentation, are typical of remains found in unprotected environments. Bleaching was typically observed beginning in the second month, and exfoliation was characteristic of bones exposed for a year to a year and a half. Articular cartilage and intervertebral discs often remained on some bone surfaces when others were showing the effects of exposure. Loss of mummified skin took approximately eight months, then bleaching and exfoliation of the bones continued until they were extensively deteriorated. In contrast, bone remained unweathered for many years in dry, shaded areas (Galloway et al., 1989). This study demonstrates that human bone weathers in the same general pattern as the mammal bone observed in other weathering experiments.

In field experiments using human cadavers in Tennessee, bones started to show bleaching within the first year, typically after the first month (Bass, 1997). After the first year, bone surfaces began to flake in moist micro-environments, and long bones developed longitudinal cracks in direct sunlight. Bass (1997) proposes that cracks occur after rapid drying in a humid environment, and that moisture may be the most influential factor in the deterioration of bone in such climates. Although these weathering rates seem to correspond to those reported by Behrensmeyer (1978) for the first two stages, it is unknown whether they are comparable for the entire sequence.

Behrensmeyer's weathering stages and corresponding times-since-death have been used by forensic investigators to determine the time-since-death of skeletonized human remains, usually to establish whether bones have been exposed for less than three years (Buchan and Anderson, 2001). Ubelaker (1997) states that taphonomic models developed in palaeontology, such as those created by Behrensmeyer, have direct utility in

forensic anthropology for estimating the postmortem interval, reconstructing the depositional environment and postmortem events, and distinguishing perimortem trauma from taphonomic damage. Buchan and Anderson (2001) caution that Behrensmeyer's research on bone weathering may not be applicable to forensic cases, since her stages were developed based on observations of large mammal bones.

In a review of forensic cases from the mid-eastern United States, Bielenstein (1990) suggests that Behrensmeyer's weathering stages can be effectively applied to determine the postmortem interval in forensic contexts. The length of time that bones from forensic cases were exposed and the weathering stages they displayed were compared to Behrensmeyer's stages and their associated postmortem intervals (see Table 1.5). None of the cases observed involved remains exposed to the environment for more than two years, so it is unclear whether bones exposed for longer would still fall within Behrensmeyer's stages. Bielenstein (1990) notes that season of deposition, local environment, ground cover, and type of clothing must be considered when assessing time-since-death from weathering data.

More research needs to be conducted using human remains in environments that correspond to those seen in forensic cases in North America, and standards for recording the weathering category for each skeletal element need to be developed before bone weathering can be used as a reliable indicator of time-since-death (Buchan and Anderson, 2001). Because the use of human remains in forensic field experiments is highly controversial, research on bone weathering can be conducted in a variety of climates using suitable animal models to correlate weathering stages with time-since-death of known forensic cases in that region.

Table 1.5. Comparison of Behrensmeyer's Weathering Stages with Known Postmortem Intervals (PMI) from Forensic Cases

# OF CASES	WEATHERING STAGE ASSIGNED TO	PMI ASSOCIATED WITH STAGE BY BEHRENSMEYER	ACTUAL PMI OF FORENSIC CASES
7	0	0 – 1 year	1 – 3 weeks to 6 – 9 months
4	1	0 – 3 years	6 – 12 months to around 2 years
1	2	2 – 6 years	4 years

Modified from Bielenstein (1990:415, Table 9)

1.2.2 Interspecies Comparison

Cultural ideas regarding the dignity of the human body preclude the use of cadavers in decomposition experiments in many places. Domestic pigs (*Sus scrofa*) have been widely used as human analogues in forensic experiments because the two species have similar hairless skin and intestinal flora, along with comparably sized thoracic cavities and biochemically similar tissues (Schoenly et al., 1991; Anderson and VanLaerhoven, 1996; France et al., 1997; Komar and Beattie, 1998). Pigs weighing 70 kg are close to average human weight and have a similar fat to muscle ratio (France et al., 1997). However, little research has been done on the ideal pig size for decomposition experiments (Komar and Beattie, 1998), and there are no studies in the literature on suitable models for the human skeleton.

Ubelaker (1978) states that, along with those of bears, cows, and horses, the bones of deer and pigs are commonly mistaken for human bones. One published study has used deer to investigate scavenging and noted striking parallels between modification to deer carcasses and to human remains in past forensic cases (Willey and Snyder, 1989).

Although deer morphology differs from that of humans, particularly in the deer's longer snout, neck, and metapodials, similarities have been observed in the movement and consumption of deer and human carcasses by canid scavengers. The thick, hair-covered hide of deer is thought to perhaps discourage consumption of some parts of the carcass, much like clothing on human bodies.

A review of the literature provides insight into whether the bones of deer and pigs are appropriate analogues for the human skeleton based on their mineral density, cortical properties, and structural characteristics. According to Genant (1994), both the density and geometry of bone affect its strength and fracture properties. Thus, the material properties of bone influence the way in which it cracks when exposed to the elements and its resistance to attritional weathering. While bone density is the measure most commonly used as a proxy for the survivability of different skeletal elements, other variables such as size, shape, and cortical thickness must also be considered (Lam and Pearson, 2004).

Size and Shape

General differences between the dimensions of bones of different species result from the tendency of skeletal elements to increase in thickness relative to their length as body size increases (Kreutzer, 1992). The limb bones of large animals are more robust than those of smaller animals, and limb bone shafts are straighter in large, heavy mammals in order to reduce stress on the bones (Kreutzer, 1992). Like other ungulates, pigs stand on fairly straight legs, and the front legs in particular are pillar-like (Liu *et al.*, 1999).

Measurements of the diameter and cortical thickness of the femur in one study revealed metric similarities between the bones of adult humans and those of pigs

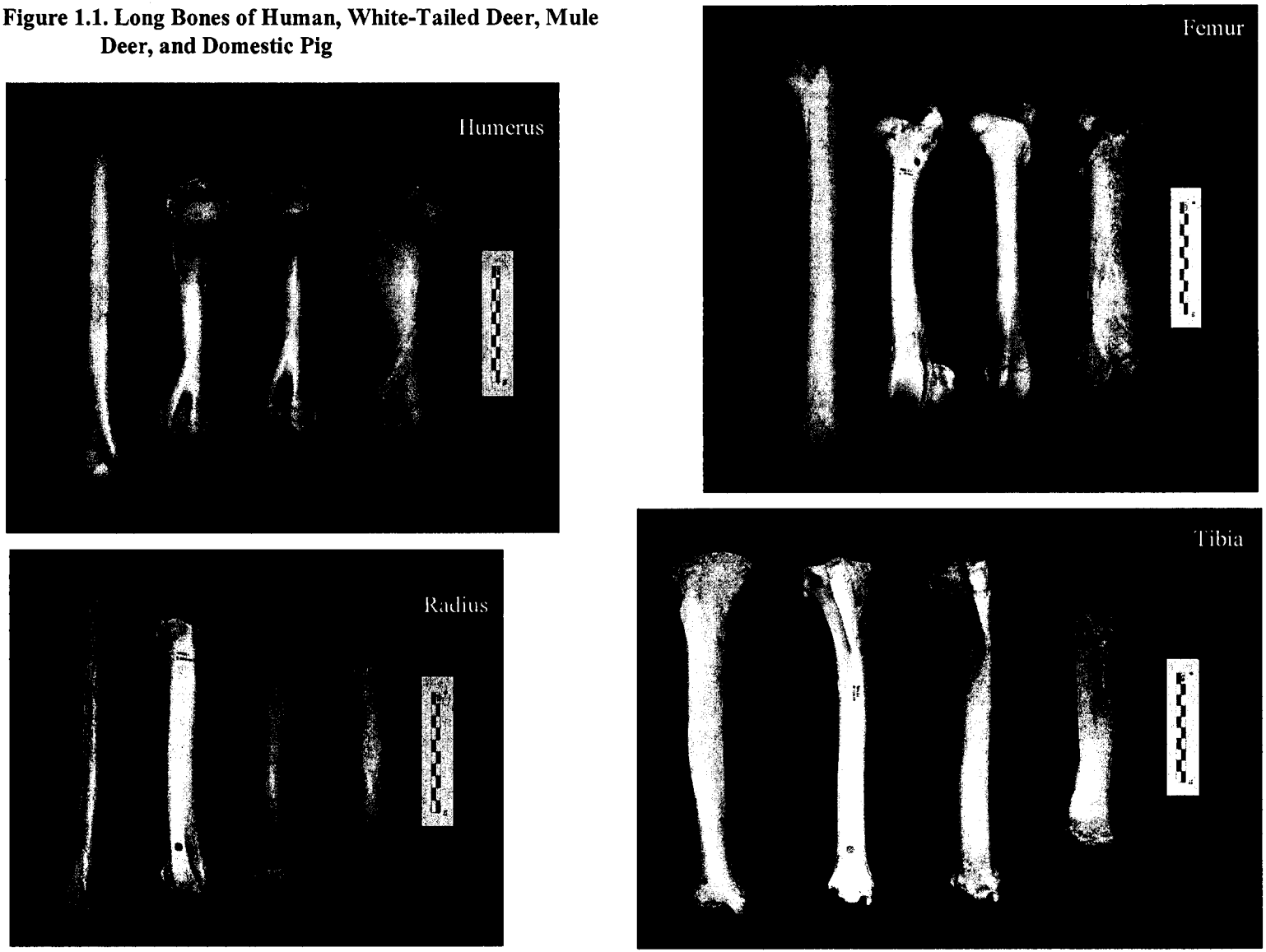
(Urbanová and Novotný, 2005). As can be seen from a simple visual assessment (see Figure 1.1), the radii and tibiae of deer are longer and more gracile than the analogous bones in pigs, making them closer in size and shape to human bones. Deer humeri and femora are also much more slender than those of pigs and have generally less robust features, causing them to be more similar to the corresponding bones in humans. Pig limb bones appear to have more surface area than deer bones of similar length, which could affect the rate at which they weather.

Intertaxonomic comparisons need to take into account factors such as breed, age, and sex, as the size and shape of bones vary significantly within species. Among the domestic and wild pigs used in previous studies, there is a large range of size variation between individuals of different ages and breeds. Richmond and Berg (1972) found few significant differences among the sampled breeds in terms of the length, circumference or weight of pig bones. However, Furugouri and colleagues (1981) found that the limb bones of some breeds are markedly larger than those of others. Additionally, the castration of domestic pigs results in significantly longer limb bones (Richmond and Berg, 1972; Reitz and Wing, 1999). Table 1.6 outlines some of the differences in limb bone length and diameter among humans, deer, and pigs.

Microstructure

According to Wang and colleagues (1998), an understanding of variation in the fracture properties, microstructure, and composition of bones of different species is necessary for the appropriate use of animal models in bone research. The number and size of osteons as well as the ultrastructure of bone affect its fracture strength (Wang et al., 1998). Thus, the way in which bone tissue is organized may affect the way different

Figure 1.1. Long Bones of Human, White-Tailed Deer, Mule Deer, and Domestic Pig



Photographs taken by author using bones from the University of Alberta's osteological and zooarchaeological collections.

Table 1.6. Comparison of Geometric Properties of Human Long Bones from Previous Studies

Study	Bone	Species	Mean Length	Mean Diameter
Hildebrand (1955)	Humerus	Deer	198	--
Skedros et al. (2003)	Humerus	Deer	--	21.7
	Radius	Deer	--	25.8
McMahon (1975)	Humerus	Deer[a]	186.8	21.9
	Femur		232.2	20.3
	Tibia		262.4	19.3
Liu et al. (1999)	Humerus	Pig	130.4	--
	Radius		140.0	--
	Femur		141.1	--
	Tibia		129.5	--
McMahon (1975)	Humerus	Pig[b]	123.7 -	--
	Femur		132.3 -	--
	Tibia		125.2 -	--
Furugouri et al. (1981)	Femur	Pig[c]	127 - 173	--
Urbanová and Novotný (2005)	Femur	Pig	--	25.6
		Human	--	27.6
Ruff and Hayes (1983, 1984)	Femur	Human[d]	410.9	23.7 - 25.6
	Tibia	Human	323.6	20.3 - 23.1
Ruff and Jones (1981)	Tibia	Human[d]	352.2 -	--
	Humerus	Human	298.0 -	--

* Either antero-posterior or medio-lateral diameter, taken at midshaft.
[a] Combines one mule deer and three white-tailed deer.
[b] Range indicates mean for 23 to 68kg pigs.
[c] Range indicates mean for 3 month old to 5 month old pigs, two different breeds combined.
[d] Range indicates mean for females to males.

skeletal elements and the bones of different species crack when exposed to weathering. Although all mammalian bone has the same basic composition, there are noted interspecies differences in the microscopic structure of compact bone, specifically in the different size, structure, and patterns of osteons and Haversian canals (Matiniaková et al., 2006). Despite age-related changes, the average diameter of Haversian canals in human bone is significantly greater than that of most animal bone (Balthazard and Lebrun, 1910; Harsányi, 1993). Considerably higher counts of Haversian systems per visual field differentiate pig and deer bone from human bone (Harsányi, 1993; Owsley et al., 1985).

Primary osteons in deer bone tend to be uniform in shape and size and are densely packed, having very little interstitial bone between osteons, while human bone is characterized by the presence of irregular primary osteons and many secondary osteons that are variable in size and shape (Owsley et al., 1985; Mulhern and Ubelaker, 2001). The lower counts of secondary osteons in deer bone indicate that it undergoes less cortical remodeling than human bone (Owsley et al., 1985; Skedros et al., 2003). Most nonhuman bone can be easily distinguished from human bone by the extensive presence of plexiform bone, a primary bone tissue defined by its symmetrical network of vascular canals in a rectangular organization in several planes (Enlow, 1966; Owsley et al., 1985; Mulhern and Ubelaker, 2001). In immature deer bone, plexiform bone is dominant near the periosteal surface, with Haversian bone forming near the endosteal margin (Hillier and Bell, 2007). In the cortical bone of adult deer, dense Haversian bone predominates as it replaces the plexiform bone, especially near the endosteal surface and in the posterior portion of the shaft (Skedros et al., 2003; Hillier and Bell, 2007). Much like human bone,

a thin layer of circumferential lamellae surrounds the periosteal surface of deer long bones (Skedros et al., 2003; Hillier and Bell, 2007).

Osteon banding, a linear organization of primary osteons in rows, characterizes some nonhuman bone, in contrast to an indistinct arrangement of primary osteons and randomly scattered secondary osteons in human bone (Mulhern and Ubelaker, 2001). The cortical bone of immature pig femora is composed of lamellar bone with alternating osteonal banding near the endosteal surface (Mulhern and Ubelaker, 2001). Immature human bone initially consists largely of lamellar bone and primary osteons, which are gradually replaced by Haversian systems and interstitial lamellae with growth and remodeling (Hillier and Bell, 2007).

Adult human bone consists primarily of secondary osteons with some non-haversian lamellae surrounding the periosteal and endosteal borders (Jowsey, 1968). The basic structural pattern of a pig's femoral cortex is primary vascular plexiform bone, with dense Haversian tissue found in the center of the compact bone and many large resorption lacunae between secondary osteons (Matiniaková et al., 2006). Dense Haversian bone tissue is also the basic structural pattern of human compact bone, although human osteons are rounder and overlap in a seemingly random manner, distinguishable from the regular arrangement of some nonhuman bone (Matiniaková et al., 2006). While the average number of Haversian canals per visual field is similar between pigs and human neonates, the average diameter of the canals is significantly smaller in pig bone (Harsányi, 1993). However, Hillier and Bell (2007) caution that, due to the variation of Haversian systems with age and anatomical location, the histological appearance of the compact bone of pigs can be very similar to that of humans.

The literature suggests that both pig and deer skeletons may be suitable models, histologically, for human bone tissue. In addition to plexiform tissue, both adult pig and deer long bones contain dense Haversian tissue, which is characteristic of human compact bone. Pig bone microstructure may be more analogous due to the comparably-sized Haversian systems and canals, as deer have significantly smaller central canals and a much lower concentration of osteons than humans.

Ultrastructure, and Fracture Properties

Microstructural features, such as the number and size of osteons, affect bone fracture properties (Wang et al., 1998). There is a strong negative correlation between the strength of bone and the percentage of Haversian system bone tissue that it contains; thus, the more secondary osteons present in remodeled bone, the lower its fracture resistance (Currey, 1959). This is due to the fact that remodeling reduces the actual amount of bone present, increases cortical porosity with larger central canals, and reduces the total mineral content of bone, causing the newly formed, less calcified bone to be weaker (Currey, 1959; Jowsey, 1966; Gaynor-Evans and Vincentelli, 1969; Martin et al., 1998). Also, the larger the number of osteons and their fragments in a given area of bone, the greater the proportion of cement substance and the lower its tensile strength, since fractures tend to follow cement lines (Martin et al., 1998).

Even for bones with similar Haversian structures, differences in ultrastructural organization of mineral and organic components can affect the way in which they fracture (Wang et al., 1998). For instance, larger collagen-mineral bundles are correlated with greater fracture resistance. Crack initiation and growth depend on the size and number of collagen fibers running through the cortical bone (Martin et al., 1998). The

orientation of collagen fibers parallel to the long axis of the bone, as well as the organization of bone into lamellae contribute to the strength and elasticity of long bones (Gaynor-Evans and Vincentelli, 1969). Remodeling may alter collagen fiber orientation and further contribute to the weakening of bone (Martin et al., 1998). In plexiform bone, circumferential cracks are more likely to travel along vascular canal networks organized in a layered fashion, decreasing the bone's fracture toughness (Wang et al:, 1998).

Bone fracture strength also depends on its chemical composition (Steindler, 1936; Wang et al., 1998). The organic content of a bone is an important factor affecting that bone's alteration and survivability when exposed to destructive weathering processes (Behrensmeyer, 1975). Bone strength is proportional to the compactness of the bone structure and its residual organic content; when collagen is removed from bone, it becomes very friable, especially when wet. The mineral composition of bone as well as the distribution and orientation of the apatite crystals also affect the strength of bone (Gaynor-Evans and Vincentelli, 1969).

Density

While the microstructure, bone matrix, and macroscopic geometry of bone contribute to its strength and affect the way it fractures, density alone accounts for 50-80% of the variance in bone strength (Genant, 1994). Density has been proposed as an important factor mediating the effect of taphonomic processes on bone (Binford and Bertram, 1977; Behrensmeyer, 1978; Lyman 1984; Elkin 1995; Ioannidou, 2003). Binford and Bertram (1977) propose that the rate of bone destruction is inversely proportional to its density and proportional to its surface area to volume ratio. Early studies on the effect of bone density on taphonomic processes were conducted by Binford

and Bertram (1977) and by Boaz and Behrensmeyer (1976); however, these studies produced variable sets of density values, likely due to inconsistencies in methodology (Lam and Pearson, 2005).

Intrataxonomic variability in bone density due to species, age, sex, nutrition, and activity levels, may make it difficult to distinguish individual from intertaxonomic differences in small samples (Steindler, 1936; Jowsey, 1964; Lyman, 1984; Ioannidou 2003; Lam and Pearson, 2004). Physiological stress during periods of gestation and lactation for females, and during the winter months for wild animals may negatively impact bone mineral density (Ioannidou, 2003).

Behrensmeyer (1975) found that bone densities are comparable for all mammals tested, although the same skeletal element in different individuals may vary due to factors such as size, age, and diet. Although the rank order pattern of density values is similar among different animal taxa, each has its own specific pattern and density values have been shown to be statistically different between species (Ioannidou, 2003). Based on this, Ioannidou (2003) concludes that the bones of different mammalian species likely survive density-mediated taphonomic processes differentially. It has been proposed that differences in the forces and loads applied to limb bones during locomotion may be reflected in bone structure; in particular, the leg bones of deer may exhibit proportionally greater mineral density than those of other animals because they must absorb greater forces in a jumping gait known as a pronk (Hildebrand, 1982; Kreutzer, 1992). This was not supported by a recent study using photon densitometry, which found that bone mineral density is not significantly different between several skeletal elements of deer

and pig (Ioannidou, 2003). Unfortunately, comparable data is not available for human bone mineral density.

Variability within species and between methods should be kept in mind when comparing bone densities. Photon densitometry measures the bulk density of only the mineral component of bone (Elkin 1995; Lam and Pearson, 2004). Photon densitometers measure mineral content across a scan site and this value is divided by the area of the scanned cross-section to give a measure of density (Elkin, 1995; Lam and Pearson, 2004). Because researchers have used different methods for determining the cross-sectional area of the scan site, the practical definition of bone density varies from one study to the next, making comparisons between different data sets problematic (Lam and Pearson, 2004). Most research using photon densitometry does not take into account the area of the medullary cavity, resulting in artificially low values for long bones. This problem is avoided in studies using computed tomography to determine density and cross-sectional geometry. Liesegang and colleagues (2002) use peripheral quantitative computed tomography to determine the density of the midshaft of the tibia and femur of domestic pigs and report density values that are higher than those reported by Ioannidou (2003) for both wild and domestic pigs.

Although many studies have focused on interspecies differences, age-related variation may be equally important in differential survival patterns based on bone density (Binford and Bertram, 1977; Ioannidou, 2003). Variation in bone mineralization with skeletal maturation makes it difficult to interpret species differences in bone density (Ioannidou, 2003). An early study by Robinson and Elliott (1957) found that adult dog bone has a greater density than that of younger animals. A more recent study found that

the bones of adult pigs generally have higher mineral densities than those of younger animals, although immature specimens consistently have higher density values at certain sites (Ioannidou, 2003). This may be explained by Binford and Bertram's (1977) findings that bone density does not increase allometrically with age; while the density of the bones of older animals is generally greater than that of juveniles, this increase is not proportional among different skeletal elements.

Lam and Pearson (2004) conclude that other variables, such as size, shape, and cortical thickness, must be examined in addition to density in order to assess resistance of bones to destructive processes. In fact, variation in bone mineral density may be largely due to variation in bone volume rather than variation in mineralization (Ruff and Hayes, 1984). According to Ruff and Hayes (1984), the locational, sex, and age-related variation in bone mineral content is due mainly to differences in cortical area.

Ruff and Hayes (1984) state that alterations in human cortical bone geometry and material properties may be more instrumental in age-related skeletal changes than density. Bone-mineral content and material strength reach a maximum in middle-age then progressively decline, doing so much more rapidly in females (Dequeker, 1976; Martin and Atkinson, 1977; Ruff and Hayes, 1984). It has been proposed that the observed decline in bone density with age is due mainly to a decrease in cortical area, rather than a loss of bone mineral content (Ruff and Hayes 1984). In fact, the thinning cortex of long bones seen in senile osteoporosis retains a high mineral content (Virtama and Telkkä, 1962).

Cortical Properties

A great number of studies have investigated the cross-sectional geometry of human long bones for the purpose of a) estimating the extent of osteoporosis and predicting fracture risk (Barnett and Nordin, 1960; Virtama and Telkkä, 1962; Dequeker, 1976; Burr and Martin, 1983; Laval-Jeantet et al., 1983; Ruff and Hayes, 1984; Bloom et al., 1984, 1987; Hsu et al., 1993; Augat, 1996; MacIntyre et al., 1999; Feik et al., 2000), b) investigating the effect of load-bearing, diet, or stress on bone remodeling (Frank, 1964; Mazess and Cameron, 1971; Martin and Atkinson, 1977; Ruff and Jones, 1981; Hatch et al., 1983; Bridges, 1989), c) gathering biomechanical and anatomical data for the design of prostheses (Ruff and Hayes, 1983; Noble et al., 1995; Stephenson and Seedhom, 1999), and d) aiding in the determination of age at death (Thompson, 1983; Narasaki, 1990; Chan et al., 2007). Unfortunately, the methods used in different investigations of bone geometry vary widely and are not always clearly explained, which complicates the comparison of the results of many studies, especially when comparing those conducted on different species.

The cortical properties of bone vary considerably with species, age, sex, and size, as well as location on the bone (Jowsey, 1964; Sedlin and Hirsch, 1966; Dequeker, 1976; Bloom, 1980; Ruff and Hayes, 1984). Activity levels and handedness also influence the distribution of compact bone (Bloom, 1980; Ruff and Hayes, 1983; Bridges, 1989). All of these factors introduce variability when comparing the cortical bone distribution of different species.

Human cortical properties peak between the ages of 30 and 40, followed by a loss of compact bone that is more drastic in women, especially after the age of 50 (Bloom and Laws, 1970; Dequeker, 1976; Martin and Atkinson, 1977; Ruff and Hayes, 1984). Males

exceed females in absolute amount of bone throughout adulthood, as indicated by cortical thickness and cortical area, although if these measures are corrected for skeletal size, women start at age 35 with as much bone as men (Dequeker, 1976). Both outer and medullary diameter enlarge after the age of 50, however, resorption at the endosteal margin is much greater in women, resulting in a net loss of cortical bone (Dequeker, 1976; Martin and Atkinson, 1977; Ruff, 1982; Burr and Martin, 1983; Laval-Jeantet et al., 1983; Ruff and Hayes, 1984; Bouxsein et al., 1994; Noble et al., 1995).

There is considerable variability in the physical properties of compact bone from different individuals within the same age group, likely due to skeletal size variation (Sedlin and Hirsch, 1966; Dequeker, 1976). Activity-related stress and strain encourages appositional growth and skeletal remodeling (Ruff, 1982). Because bone is distributed to minimize strain under loading, regions subjected to relatively high mechanical stress in life show greater increases in total subperiosteal and smaller decreases in cortical bone area with age, even within a single bone (Ruff, 1982; Ruff and Hayes, 1983). Cortical bone features vary along the length of the shaft of limb bones (Ruff and Hayes, 1983). In humans, cortical thickness is consistently higher in the bones of the upper limb on the dominant side (Bloom, 1980).

An interspecies comparison of cortical properties is valuable not only to forensic anthropology, but can also contribute to the disciplines of zooarchaeology and palaeoanthropology. Forensic anthropological investigations often depend on the ability to distinguish between bone fragments of human origin and those of other species (Urbanová and Novotný, 2005). Many taxa share similar bone morphology, and the frequently fragmented condition of many bone samples may limit the discriminative

capability of morphological characteristics such as bone size and shape (Urbanová and Novotný, 2005). In such cases, a look at the microstructure and cortical properties of bone fragments can contribute greatly in discriminating human from animal bone.

1.3 Research Questions

Previous research has revealed many factors that affect bone weathering, such as different climates, freeze-thaw cycles, micro-environmental conditions, skeletal element, animal taxa, carcass size, animal age, scavenger activity, and initial decomposition. Some of these have been more well-researched than others, and further study has been suggested in order to examine many of these variables. Several studies have found that bone weathering in different climates and situations follows the same progression as that initially described by Behrensmeyer (e.g. Gifford, 1984; Galloway et al., 1989; Bielenstein, 1990; Bass, 1997); however, other studies have observed weathering patterns and rates that diverge from the widely accepted stages (e.g. Haynes, 1980; Todd, 1987; Tappen, 1994; Andrews, 1995).

The present study will add to the limited body of knowledge on bone weathering in a cold climate. This experiment is more controlled than previous studies conducted in similar environments in order to attempt to isolate the effects of some of the factors that affect weathering processes. Deer and pigs were chosen as models for human bone weathering based on similarities of some skeletal elements of each species with the corresponding bones in humans. Because the weathering rates of different skeletal elements are being compared, it was important to have a similar time of exposure for all bones in the skeleton. Weathering stages were correlated with time since exposure for different groups of skeletal elements and for different species, and the weathering rates

were examined in the context of seasonal and diurnal variation in temperature and precipitation. Weathering stages correlated with known post mortem intervals from previous studies were compared to the results obtained in this experiment. In addition, past forensic cases from the Edmonton region involving skeletal remains with known times of exposure were reviewed to see if the weathering rates observed in deer and pig bones can be associated to those seen in humans.

This thesis follows a paper-style organization, and each chapter is meant to stand independently. Chapter 2 details an interspecies comparison of the cortical bone properties of human, deer, and pig, while Chapter 3 deals with the field experiment on bone weathering. The research questions being investigated include:

1) Are deer and pigs skeletons suitable human analogues based on their geometric and cortical properties?

2) How does weathering affect skeletons of different species, age, and size?

3) How does weathering affect different skeletal elements?

4) What are the effects on bone weathering of climate, micro-environment, and season of deposition?

5) What are the effects of scavenger activity and manner of exposure of the bones?

6) Can weathering stages be correlated with postmortem intervals?

7) Are weathering rates of deer and pig bones comparable to those of human remains?

The results of this research will contribute to an understanding of bone weathering and the various factors that alter its rates of progression, and can eventually be applied to determining the post-mortem interval and reconstructing taphonomic processes in forensic cases in cold climates.

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2. An Interspecies Comparison of Bone Properties: Cortical Density and Cross-Sectional Geometry of Human, Pig, and Deer Long Bones

2.1 Introduction

Experiments in forensic taphonomy often make use of animal carcasses as human models due to the ethical issues and practical difficulties involved in obtaining human bodies for these kinds of studies (Schoenly et al., 1991; Komar and Beattie, 1998). Domestic pigs, *Sus scrofa*, have been widely used as human analogues in decomposition experiments because they have relatively hairless skin and similarly sized torsos, and have digestive tract fauna similar to that found in humans (Schoenly et al., 1991; Anderson and VanLaerhoven, 1996; Komar and Beattie, 1998). In one exception, a taphonomic experiment used deer as models, instead of pigs, in order to investigate canid scavenging of exposed bodies (Willey and Snyder, 1989). The authors discovered striking similarities between scavenger alteration of deer carcasses and that of human remains in forensic cases. Although research has been conducted to investigate the size of pig best suited to serve as a model for human soft tissue decomposition (e.g., Komar and Beattie, 1998), no studies have investigated what size and species of animal should be used as a model for the deterioration of human bone. The bones of deer and pigs are often mistaken for human bones by untrained observers (Ubelaker, 1978). The present study examines whether the bones of deer and pigs are suitable human analogues based on the cortical properties and metric characteristics of the long bones of each species.

The material properties of bone affect the way in which it reacts to attritional processes. The density and geometry of bone contribute to its strength and the way in which it fractures (Genant, 1994), and thus, affect the way in which it cracks when exposed to weathering agents. Density has been proposed as an important factor

mediating the differential destruction of bone by taphonomic processes (Binford and Bertram, 1977; Behrensmeyer, 1978; Lyman 1984; Elkin 1995; Ioannidou, 2003). While bone density is the most commonly used proxy measure of the survivability of different skeletal elements, other variables such as size, shape, and cortical thickness must also be examined in order to assess the resistance of bones to attritional forces (Lam and Pearson, 2004).

Many studies have investigated the cross-sectional geometry and/or density of human bones in order to establish biomechanical and anatomical data for designing prostheses (e.g., Ruff and Hayes, 1983; Noble et al., 1995; Stephenson and Seedhom, 1999), to investigate the effect of physical activity, nutrition, or stress on bone growth and remodeling (e.g., Mazess and Cameron, 1971; Martin and Atkinson, 1977; Ruff and Jones, 1981; Bridges, 1989), to estimate the extent of osteoporosis in the skeleton or to predict fracture risk (e.g., Barnett and Nordin, 1960; Virtama and Telkkä, 1962; Dequeker, 1976; Burr and Martin, 1983; Laval-Jeantet et al., 1983; Ruff and Hayes, 1984; MacIntyre et al., 1999; Feik et al., 2000), or to aid in the estimation of age at death (e.g., Thompson, 1983; Narasaki, 1990; Chan et al., 2007). Studies on the densitometric and geometric properties of animal bone have been conducted in diverse fields such as zooarchaeology (Lyman, 1984; Purdue, 1987; Kreutzer, 1992; Elkin, 1995; Ioannidou, 2003), biomechanics (Wang et al., 1998; Skedros et al., 2003), comparative anatomy (Jowsey, 1968; McMahon, 1975), agricultural science (Cuthbertson and Pomeroy, 1962; Richmond and Berg, 1972; Field et al., 1974; Furugouri, 1981; Liu et al., 1999; Liesegang et al., 2002), and forensic science (for the investigation of poaching as well as homicide) (Hildebrand, 1955; Owsley et al. 1985; Urbanová and Novotný, 2005).

However, the methods used in these studies vary widely and are sometimes inadequately described, making comparisons between authors problematic, especially when comparing data from different species. Relatively few studies have compared the material properties of human and animal bone (for exceptions, see Jowsey, 1968; Wang et al., 1998; Urbanová and Novotný, 2005).

For this study, measurements were taken directly and consistently on the long bones of humans, deer, and pigs. Comparative measurements of the humerus, radius, femur, and tibia of each species served to compare the length, diameter, cortical density, cross-sectional area, and cortical thickness of these bones, in order to investigate whether pig and deer are suitable as human models in taphonomic experiments.

2.2 Methods

Preparation

The human sample for this study consisted of the long bones from five female and five male embalmed cadavers donated through the Anatomical Gifts Program of the University of Alberta's Division of Anatomy. The average age of the donor population was 76.7 years, ranging from 66 to 93 years.

The humerus, radius, femur and tibia were dissected from each individual. Each of these long bones has been the focus of research on the density and/or cortical properties of human, deer, or pig bone (as mentioned above). Advantages of using long bones include their thick compact cortices, which are easily distinguished from adjacent trabeculae, and the ease with which sites can be measured consistently across different skeletal elements and different species. The ulna and fibula were not examined as the

shafts of these bones are much diminished in pig and deer and are not comparable to the analogous bones in humans.

In order to avoid any differences due to bilateral asymmetry, long bones from the left side were selected for study. One female individual had undergone hip replacement surgery on the left side, thus, the right femur was used in this case. One male individual was eliminated from the sample due to extensive periosteal reaction on both tibiae and some reactive bone formation on the femur. Some of the individuals may have been immobilized for some time before death; listed causes of death included respiratory arrest, renal failure, pneumonia, lymphoma, brain and lung cancer, and, most commonly, cardiovascular disease. No other bone lesions or pathologies were observed.

The humerus, radius, femur, and tibia from two juvenile and two adult deer were obtained from the zooarchaeological collection of the University of Alberta's Department of Anthropology. The deer were either *Odocoileus hemionus* (mule deer) or *O. virginianus* (white-tailed deer), although, since the individual skeletons were not identified to species, these were treated as a single group. The specimens had been previously boiled to remove soft tissue and bone grease. One skeleton was slightly weathered and showed signs of animal gnawing, indicating that it had been exposed prior to processing. The remaining skeletons had been processed immediately following dissection. Species, sex, and age of the deer were largely unknown; one of the adults was a female mule deer.

The long bones of pigs used in previous decomposition experiments were collected from the University of Alberta's experimental farm. Six femora, five tibiae, four humeri, and three radii were used. Breed, sex, and age were unknown, although all

long bone epiphyses were unfused. The pigs weighed between 70 and 90 lbs (Crystal Samborski, personal communication). All pig carcasses represented industry casualties; no animals were euthanized for the purposes of this study. The carcasses had been exposed for less than one year and the bones showed no signs of bleaching or cracking. A number of the bones had been gnawed by scavengers and many were missing epiphyses. Although some of the carcasses had been exposed to fire, none of the bones used for this experiment were charred.

The bones were cleaned of any adhering soft tissue and periosteum using forceps. Prior to sectioning, the anterior and lateral surfaces were marked with indelible ink and the proximal end was indicated with an arrow. The antero-posterior plane was defined as passing through the mid-points of the shaft with the bone resting naturally on its posterior aspect on a flat surface (see Stephenson and Seedhom, 1999). The medio-lateral plane was then defined as being perpendicular to the antero-posterior plane, again, passing through the mid-points of the shaft.

The length of each complete bone was measured using either a carpenter's square or a fixed graph and a moveable upright. Buikstra and Ubelaker's (1994) standard measurements for maximum length of the humerus, femur, and radius, and length of the tibia were adjusted for use with deer and pig bones. For the cadaveric bones, cartilage remained on the joint surfaces and measurements were taken to the nearest millimeter. For deer and pig bones that were missing epiphyses or had been damaged by carnivore gnawing, length was estimated by comparison with reference samples.

All bones were marked at mid-shaft (50% of total length) and a subsample of each species (28 human, 8 deer, and 4 pig bones) were also marked at 35% and 65% of the

total bone length. Bones were then sectioned perpendicular to the longitudinal axis using a bandsaw or fine-bladed hacksaw. A water-cooled diamond circular saw was used to cut smaller sections. Marrow and superficial trabeculae were removed using forceps and a blunt probe. Bone sections were ground to a thickness of approximately 1cm using a Buehler Isomet polisher/grinder. Samples were then weighed, soaked in distilled water for 24 hours, weighed again, and dried in an oven at 90°C for 24 hours.

Bone density was defined in the classic sense: as the ratio of the mass of a substance to its volume, which was measured using the differential volumetric method (Taylor, 1967). Thus, cortical density here is the amount of compact bone per unit volume, and not the mineral content of the bone (see Broman et al., 1958). Cortical density as determined in this study can be considered true density, as it is exclusive of pore space (see Lam and Pearson, 2004). A simple measure of density as the ratio of the dry weight of the cross-section to its volume was calculated in grams per milliliter, or cubic centimeter.

Dried samples were weighed to the nearest tenth of a gram and volume was determined by water displacement using a graduated cylinder, always reading from the bottom of the meniscus. Depending on the width of the section, graduated cylinders with 0.5, 1, or 2 mL gradations were used. All determinations were made at room temperature and care was taken to dislodge air bubbles adhering to the submerged sections (see Quincy Woodard, 1962; Blanton and Biggs, 1968).

Analysis

Each bone section was scanned and photographed, and the maximum medio-lateral diameter of each bone section was measured using digital calipers accurate to

0.01mm. Cortical dimensions of the cross-sections were measured using image analysis software (Image J, version 1.37v, National Institute of Health). Brightness and contrast were adjusted to include the entire cortical bone surface when the binary image was created using the automated threshold (see Figure 2.1). The boundary of the medullary cavity was defined as the innermost border of the solid cortical layer, not including any isolated pixels.

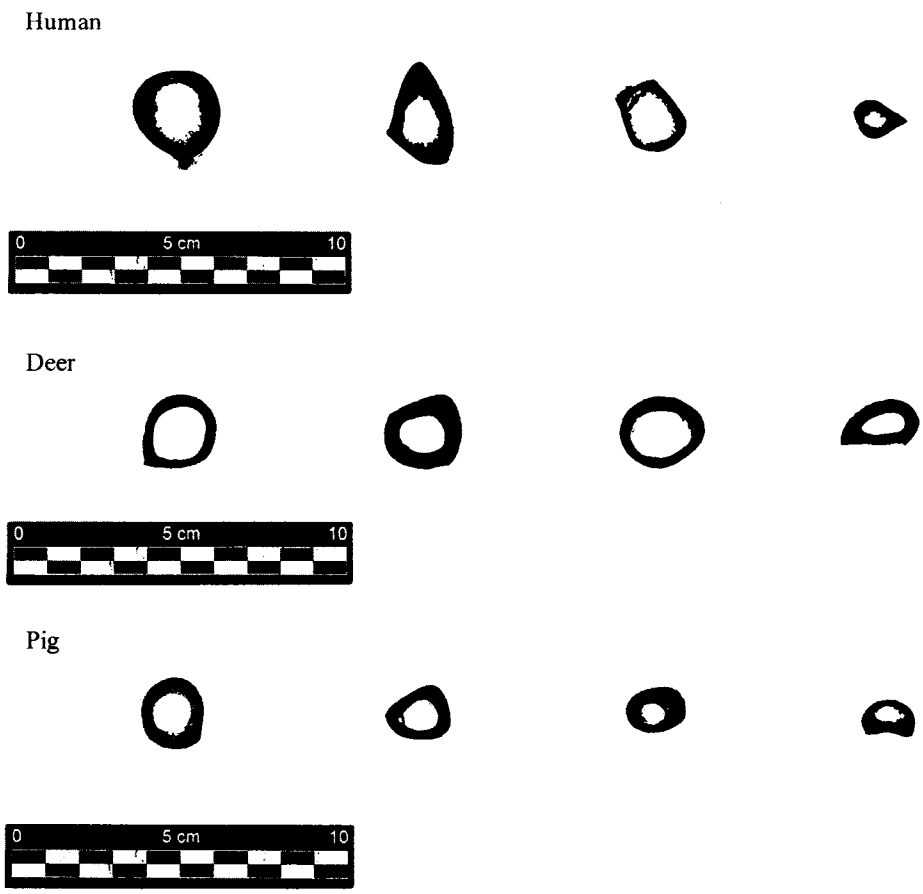
The proximal aspect was analyzed for most cross-sections, although, in cases where ink staining or chipping of the sample interfered with conversion to a binary image, the distal aspect was used. Total cross-sectional, or sub-periosteal, area (TA) and cortical area (CA) were calculated. The centroid, or center of area, of the periosteal outline was calculated (see Feik et al., 2000) and this point was used as a reference for the location of the measurement of anterior, posterior, medial, and lateral cortical thicknesses as well as medio-lateral and antero-posterior diameters (Martin and Atkinson, 1977). The medullary diameter was subtracted from the outer diameter of each section to determine medio-lateral and antero-posterior combined cortical thickness (CCT).

2.3 Results

Various indices reflecting the relative amount of cortical bone were derived from the basic measurements. To compensate for differences in body size, cross-sectional area was standardized by maximum medio-lateral diameter (CA/MLD) (see Dequeker, 1976). The cortical index expressed the ratio of combined cortical thickness to total width of the bone (see Barnett and Nordin, 1960). The percent cortical area was calculated by dividing

Figure 2.1. Interspecies Comparison of Cross-Sections from Femur, Tibia, Humerus, and Radius

Figure 2.1. Cross-Sections of Femur, Tibia, Humerus, and Radius



cortical area by the total subperiosteal area (CA/TA), reflecting the relative amount of cortical bone in a given cross-section (see Bouxsein et al., 1994; MacIntyre et al., 1999).

While the long bones of deer are more similar to those of humans in some respects, those of pigs are more comparable in others. All of the deer bones measured are closer in length to those of humans, with pig long bones being far shorter. Although the average length of deer femora is much closer to that of humans, the cortical properties of pig femora are closer to those of humans (see Figure 2.2). In contrast, when the tibiae are examined, cortical density and nearly all geometric properties of deer bones are more similar to those of humans, with the exception of medio-lateral combined cortical thickness (ML-CCT).

Interspecies differences in the humerus and radius are more inconsistent. Although the pig and human humeri are more similar in terms of cortical density and antero-posterior combined cortical thickness (AP-CCT), those of deer and humans are closer in medio-lateral combined cortical thickness (ML-CCT) (see Figure 2.2). While the humeral cross-sections of pigs and humans are also more similar in absolute cortical area, the humeri of deer and humans are more similar when cortical area is standardized by medio-lateral diameter (CA/MLD) and by total area (CA/TA) (see Figure 2.3).

The radii of pigs and humans are more comparable in terms of absolute cortical area and cortical area standardized by medio-lateral diameter (CA/MLD), but the same does not hold true for cortical area standardized by total area (CA/TA), for which deer and humans are more alike (see Figure 2.2 and 2.3). While the radii of pigs and humans are more comparable with respect to both medio-lateral and antero-posterior combined

Figure 2.2. Standardized Cortical Area, Medio-Lateral and Antero-Posterior Combined Cortical Thickness, and Cortical Density of Human, Pig, and Deer Long Bones

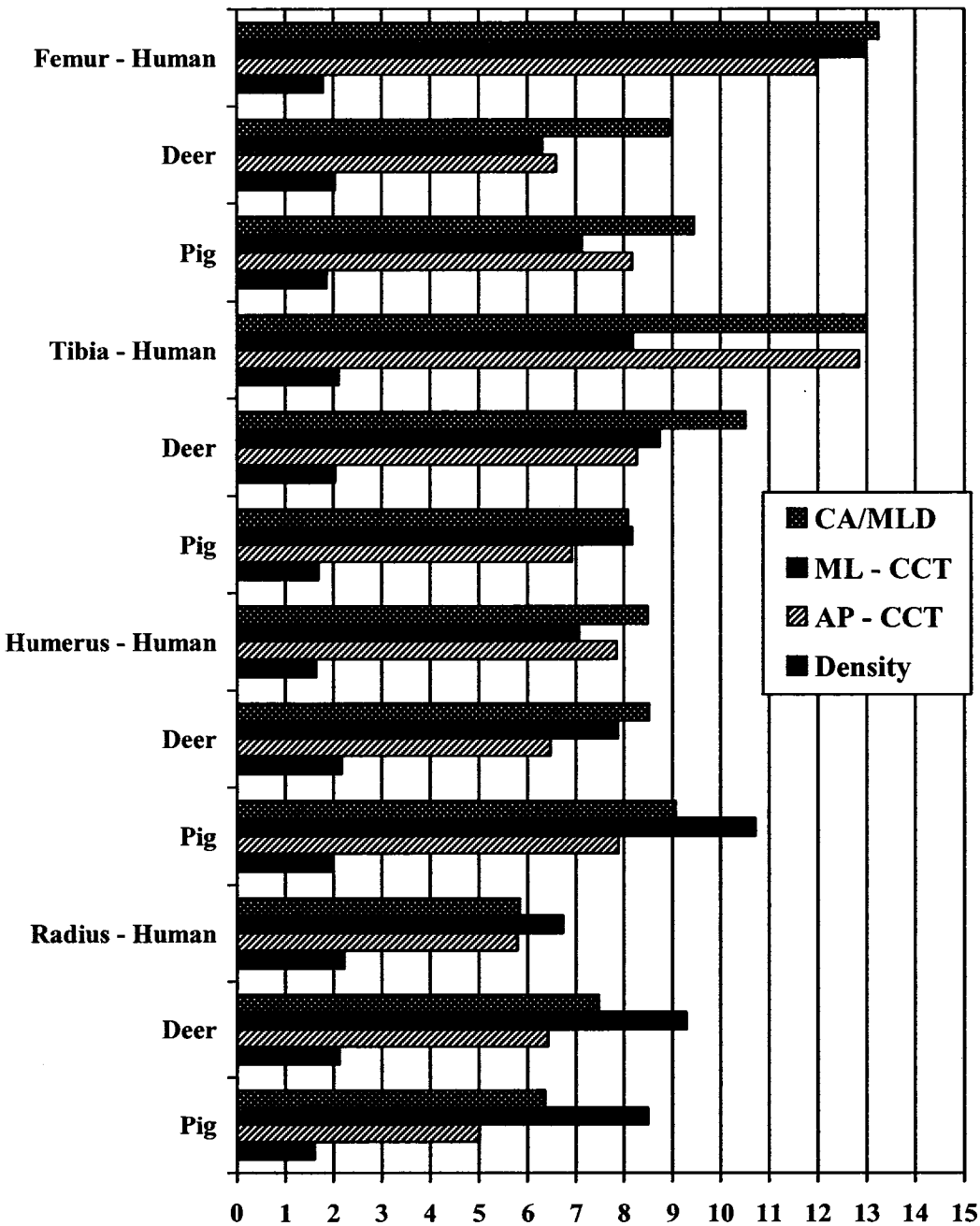
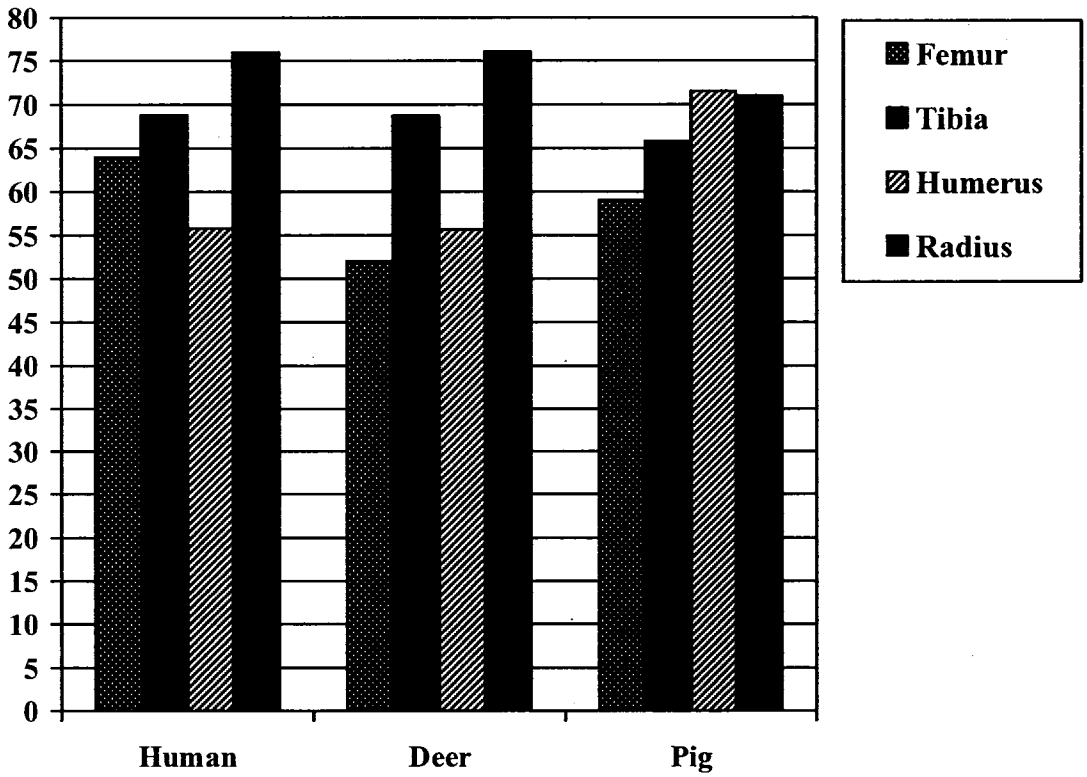


Figure 2.3. Cortical Area Index* of the Long Bones of Human, Deer, and Pig



* 100 CA/TA

cortical thicknesses (ML- and AP-CCT), deer and human radii are closer with respect to cortical density (see Figure 2.2).

2.4 Discussion

The density and geometry of bone vary considerably with age, sex, and size as well as location on the bone and species of the animal (Jowsey, 1964; Sedlin and Hirsch, 1966; Dequeker, 1976; Binford and Bertram, 1977; Bloom, 1980; Ruff and Hayes, 1984). Since the distribution of cortical bone varies in response to stresses and strains developed under loading, activity levels and handedness can also affect cortical thickness and area (Bloom, 1980; Ruff and Hayes, 1983; Bridges, 1989). All of these factors add variability to the data sets being compared in this study.

In humans, bone mineral content and cortical properties peak around the age of 30-40 years, followed by a progressive decline that is far more pronounced in women, accelerating after the age of 50 (Dequeker, 1976; Martin and Atkinson, 1977; Ruff and Hayes, 1984). Subperiosteal and medullary diameter increase significantly after the age of 50 in both sexes, however, the expansion of the medullary cavity due to endosteal bone resorption is much greater in women, leading to a net loss of cortical area and thickness (Dequeker, 1976; Martin and Atkinson, 1977; Ruff, 1982; Burr and Martin, 1983; Laval-Jeantet et al., 1983; Ruff and Hayes, 1984; Noble et al., 1995). Since all of the donors in this study were 66 or older, one would expect the cortical density, thickness, and area of the human sample, especially the females, to be lower than that of an average adult population. However, a comparison with previously reported data (see Table 2.1) reveals that most of the measurements of cortical area from this study fall within the range or slightly above the published data (Ruff and Jones, 1981;

Table 2.1. Comparison of Geometric Properties of Human Long Bones from Previous Studies

Study	Bone	Section	Mean Diameter (mm)	Present Study	Mean Cortical Area (mm^2)	Present Study	Cortical Area Index (100CA/TA)	Present Study
Ruff and Hayes (1984) archaeo-logical sample	Femur	Distal third	24.6-26.6*	27.6	246-325	333.8	--	--
		Midshaft	23.7-25.6	26.8	287-366	374.0	--	--
		Proximal third	24.6-27.3	27.1	291-383	384.9	--	--
	Tibia	Distal third	20.1-22.5	19.5	182-261	252.9	--	--
		Midshaft	20.3-23.1	19.1	203-299	296.6	--	--
		Proximal third	20.7-23.7	21.3	201-309	318.7	--	--
Ruff and Jones (1981) -x-ray	Tibia	Distal third	--	--	253.7-367.9	252.9	68.2-76.1	72.4
	Humerus	Distal third	--	--	153.8-218.7	170.7	71.1-77.6	60.3
Bridges (1989)[n.b.] -CTscan	Femur	Midshaft	--	--	323-444	374.0	--	--
	Humerus	Midshaft	--	--	157-209	175.2	--	--
Bouxsein et al. (1994) -CTscan	Radius	Distal third	12.5-13.1	12.7	74.3-83.8	81.9	73-83	75.0
Laval-Jeantet et al. (1983)	Humerus	Proximal third	19.1-22.5	20.0	122-177	165.9	--	--

* Ranges show female and male means.

[n.b] Two different archaeological populations combined.

Laval-Jeantet et al., 1983; Ruff and Hayes, 1984; Bridges, 1989; Bouxsein et al., 1994). The mean cortical thickness for the femoral midshaft was found to be 6.4 mm, which corresponds to that reported by Jowsey (1966) for adults aged 30 to 39.

Periosteal apposition with age causes an increase in the total cross-sectional area and bone width, although it does so to varying degrees in different bones (Bouxsein et al., 1994). Thus, some of the indices used in this study, such as the cortical area index (CA/TA) and cortical area normalized by bone diameter (CA/MLD), may have been somewhat skewed in the human sample. In particular, expansion of the cortex decreases the ratio of cortical area to total subperiosteal area, even when actual loss of cortical area is relatively small (Ruff and Hayes, 1984). However, a look at previously reported data indicates that the values reported here for the cortical area index (CA/TA) fall within those found in past studies (see Table 2.1).

Although none of the causes of death were associated with primary skeletal disease, secondary pathological involvement of the skeleton may have been implicit in some individuals. For instance, past research has excluded individuals with chronic renal failure from skeletal samples as it can lead to significant bone loss (Ruff, 1984). Several of the bones showed evidence of increased porosity once sectioned, thus lowering the average cortical area and density for the human sample. Ruff and Hayes (1983) state that arthritis, seen as marginal lipping, osteophyte formation, and eburnation, can be considered a "normal" part of the aging process and is present to some degree in most older individuals, and is thus not sufficient cause for eliminating bones from a sample.

Intrataxonomic variability in bone density, due to age, sex, nutrition, and activity levels, may make it difficult to discern intertaxonomic differences in small samples

(Lyman, 1984; Lam and Pearson, 2004). This did not seem to present a problem in the present study, perhaps due to the fact that the sample for each species was fairly homogenous. While there is a fairly wide range in the size of human long bones, there is extensive overlap of cortical properties within each species. Among the domestic and farmed wild pigs in the literature reviewed, there is a large range of size variation between individuals of different ages and breeds. While Richmond and Berg (1972) found that there were few significant differences among breed groups in the length, circumference or weight of pig bones, Furugouri and colleagues (1981) found that the limb bones of Landrace pigs were much larger than those of Middle Yorkshire pigs. The breeds of the domestic pigs used in this experiment are unknown, although there does not appear to be marked variation among the long bones of individual pigs. For the purposes of this study, the two deer species are considered as a single group. Although the maximum weight for white-tailed deer is less than that of mule deer (Kreutzer 1992), there is significant overlap in the size of the limb bones of these species and they are often indistinguishable.

Although the rank order pattern of density values is similar among different animal taxa, each has its own specific pattern and density values have been shown to be statistically different between species (Ioannidou, 2003). Binford and Bertram (1977) speculate that variation in density ascribed to taxonomic differences may be due, rather, to size differences among species. A previous study using water displacement reported human cortical bone densities for fragments of the humerus, femur, and tibia of individuals aged 5 to 72 years ranging from 1.79 to 1.93 g/cm^3 (Quincy Woodard, 1962). These values fall within the range of cortical density values (including the radius) from

this study, between 0.9 and 2.9 g/cm^3. Since photon densitometry measures the bulk density of only the mineral component of the bone (Elkin 1995; Lam and Pearson, 2004) the results of the present study cannot be compared with the density values reported by Lyman (1984) for deer or Ioannidou (2003) for pig. While bulk density may better approximate a bone's resistance to taphonomic processes such as fluvial transport (Behrenmeyer 1975; Lyman, 1984), cortical density may provide a better approximation of susceptibility to surface cracking and flaking caused by weathering processes.

Variation in bone mineralization with skeletal maturation makes it difficult to interpret species differences in bone density. An early study by Robinson and Elliott (1957) found that bone from adult dogs had a greater density than that of younger animals. A more recent study found that the bones of adult pigs generally had higher mineral densities than those of younger animals, although immature specimens consistently had higher density values at certain sites, including the proximal and mid-shaft locations on the humerus and femur (Ioannidou, 2003). This may be explained by Binford and Bertram's (1977) findings that bone density does not increase allometrically with age. While the density of the bones of older animals is generally greater than that of juveniles, this increase is not proportional among different skeletal elements (Binford and Bertram, 1977).

Early studies on bone density and taphonomy were conducted by Binford and Bertram (1977) and by Boaz and Behrensmeyer (1976) using water displacement of whole bones. Water displacement has also been used in more recent studies to measure the volume of bone sections analyzed by photon densitometry (see Elkin, 1995; Cruz and Elkin, 2003). Bone density studies using water displacement have produced variable sets

of density values, likely due to inconsistencies in methodology (Lam and Pearson, 2005). It has been observed that air pockets trapped within the bone could decrease the precision of volumetric displacement measurements (Broman et al., 1958). In the present experiment, bones were sectioned, thus, there were no large pore spaces in which pockets of air could be trapped. In one study, air bubbles adhering to submerged cortical bone fragments were estimated to lower measured volume by 0.1 to 0.2% (Quincy Woodard, 1962). Deer bone was observed to have the least amount of trabecular bone in which air bubbles could be retained, while the juvenile pig bone and more porous sections of human bone could have held more trapped air. Fresh bone may have had pores blocked by organic matter, thus, water may have permeated weathered bone more fully, affecting water displacement measurements (Behrensmeyer 1975).

The location of the cross-sections at 35, 50, and 65% of total bone length may have led to the measurement of anatomically different skeletal regions in different species, with different proportions of trabecular and cortical bone between subjects of different size (see Sievänen et al., 1996). However, the use of anatomically defined locations might also have introduced variation due to the differences in the features of the bones of each species.

The number of different indices proposed by past researchers suggests that none has proved to be quite satisfactory (Dequeker, 1976). While the standardization of geometric data by bone length has been advocated by some authors (see Bouxsein et al., 1994), other studies have found that normalizing by length does not significantly reduce inter-individual variation and may actually distort true patterns of variability (Ruff and Hayes, 1983). In addition, geometric data cannot be standardized using length if bones

are fragmentary or carnivore-damaged. In the present study, size was compensated for using bone diameter and total cross-sectional area, as suggested by previous researchers (Dequeker 1976; Mazess and Cameron, 1971; Bouxsein et al., 1994; MacIntyre et al., 1999). It is unclear, however, which of these measures reflects the "true" pattern of variability.

Measurement error can be introduced in the determination of the cortical/trabecular bone interface (Minns et al., 1975). Pixels at the endosteal border and within intracortical porosities are converted to either black or white when the binary is created, thus, the automatic threshold determined by the program either includes or excludes trabecular bone and small porosities. This creates variation among different samples as bone color varies from one section to the next and brightness and contrast are not adjusted in exactly the same way for each specimen. Areas of trabecular bone or of very porous cortical bone were largely excluded in the binary image (see Figure 2.1). Thus, the cancellisation of cortical bone, a common feature of osteoporosis, was accounted for and only the homogenous compact bone was included in cortical area calculations (see Barnett and Nordin, 1960).

The nature of the sample in this experiment varied from cadaveric human bone, to curated deer bone, to exposed pig bone. Past research indicates that embalming does not appear to have an effect on the density of compact bone (Blanton and Biggs, 1968). While the human bones were dissected from embalmed cadavers, the deer bones had been boiled, resulting in fine cracks and cortical bone that was friable in some cases. The pig bones had been exposed to weathering processes, and though no cracks were observed, flaking of the outer cortical layer was sometimes seen when the bones were

placed in water after having been dried. Boiling and weathering may cause similar deterioration of the organic component of the bone, thus affecting cortical density measurements. It is also possible that the pig bones, exposed to minerals and various micro-organisms, may have contained inclusions that could also alter density.

Cortical density could also have been slightly affected by the differential water content of the embalmed, processed, and weathered bones. Although all bone sections were soaked and dried for the same period of time, some may have retained more water than others. The embalmed bone clearly retained more bone grease and remnants of adhering soft tissue than the pig or deer samples, and this additional organic matter may have increased bone mass to some degree. However, a previous study found no significant differences between the dry and rehydrated weights of bone either before or after fat was extracted (Robinson and Elliott, 1957).

Ideally, bone samples should be obtained from individuals of different ages, as cortical properties change markedly throughout life. Both adult and juvenile deer were used in this study. White-tailed deer are known to attain approximately 90% of their adult bone size by six months of age (Purdue, 1987). A separation of the data for juveniles and adults in this study did not reveal different trends than the pooled measurements, so deer of all ages were considered as a single group. Unfortunately, most of the human sample was from elderly individuals, while all pig bones were juvenile, making comparisons somewhat problematic due to age-related variation in cortical properties. Additionally, adult and juvenile bones may have differential rates of water uptake, causing variation in volume measurements. More research needs to be conducted with a larger, more representative sample of both adult and juvenile populations of each species.

Other important factors that need to be compared among different species include bone histology, structural organization, and fracture properties, which also affect how bones are modified by attritional taphonomic processes. The bone of other species, such as black bears, domestic sheep, or large dogs, could also be investigated as models for human skeletons. Although long bones were the focus of this study, similar research on the density and geometric properties of other skeletal elements would be valuable.

2.5 Conclusion

The results of this study imply that both deer and pig skeletons can serve as suitable models in forensic experiments based on their geometric and densitometric similarities to human bone. It has been suggested that the long bones of most adult mammals that are comparable in size to humans are generally thicker with more compact cortices (Ubelaker, 1978). This was not found to be the case for the medium-sized adult deer skeletons used in this study; while some deer long bones had a greater diameter and/or cortical thickness than the corresponding human bones, others did not. Cortical bone density was equally variable among different species, with the femur and humerus of deer being more similar to those of humans, and the tibia and radius of pigs being closer to the corresponding human bones. Although the length of deer long bones is more similar to that of human bones, more research is needed on comparisons using adult pig bones.

This research represents the only interspecies comparison of bone properties aimed at justifying the use of animal models in forensic experiments using skeletal remains. The results have been applied to a taphonomic experiment on bone weathering, and could also be of value for studies on damage caused to bones by scavenging or trauma.

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3. Bone Weathering and Time-Since-Death in a Cold Climate

3.1 Introduction

Although bone weathering has been studied in palaeoecological and archaeological contexts (e.g. Brain, 1967; Miller, 1975; Behrensmeyer, 1978; Haynes, 1981; Gifford, 1984; Todd, 1987; Tappen, 1994; Andrews, 1995), little research has been conducted on this taphonomic process in a forensic context (see Galloway et al., 1989 for an exception). Weathering involves the physical destruction of bone through the decomposition of its organic and inorganic components as caused by exposure to saturation, desiccation, and sunlight as well as changes in temperature (Miller, 1975; Behrensmeyer, 1978; Shipman, 1981; Ubelaker, 1997).

Weathering is one of the most destructive taphonomic processes to act on skeletal remains (Phoca-Cosmetatou, 2002); it can be identified by the characteristic damage it causes to skeletal elements. Fluctuations in temperature and moisture cause fine cracks to form parallel to the alignment of collagen fibers, and these fissures deepen over time (Tappen and Peske, 1970; Behrensmeyer, 1978; Shipman, 1981). Weathering cracks increase the bone surface area exposed to the elements, encouraging further disintegration (Grupe and Dreses-Werringloer, 1993). Weathering also causes flaking of the thin outer layers of bone and, eventually, erosion of the external surface (Behrensmeyer, 1978). Bones become bleached and chalky with prolonged exposure to sunlight due to the degradation of their organic components (Brain, 1967; Miller, 1975; Galloway et al., 1989; Ubelaker, 1991; Andrews, 1995). In the more advanced stages of weathering, cracks extend into the marrow cavity and splinters form, eventually causing the bone to fall apart *in situ* (Behrensmeyer, 1978).

Several variables affect the progression of bone weathering, and there is a general consensus that most of these factors require further research. For instance, detailed information on the relative weathering rates of specific skeletal elements is not available (Lyman and Fox, 1997). According to Todd and colleagues (1987), additional experimental research is needed to determine the weathering characteristics of different types of bones.

Although different micro-environments appear to affect weathering patterns, the amount of variation required to significantly alter weathering rates is unknown (Lyman and Fox, 1997). Gifford (1981) notes that bones may weather more rapidly in some areas, such as the North American Plains, and that it should be possible to correlate rates of bone weathering with different climates. While the sequence of bone deterioration is similar in many ways across diverse environments, the length of time it takes for bones to pass through each weathering stage may differ greatly, depending on mean annual temperatures, precipitation and humidity levels, and sunlight intensity (Haynes, 1981). Relatively little is known about the way bone weathers in different habitats and further research in a broad range of environments is necessary, especially in climates where the effects of freeze-thaw cycles can be investigated (Behrensmeyer, 1978).

The effects of the initial conditions of decomposition on subsequent weathering are unknown (Behrensmeyer, 1978). Bones are exposed to weathering agents after soft tissues detach from the skeleton, thus, the time of exposure depends on the way in which hide and other tissues decompose (Hill, 1979; Micozzi, 1986; Lyman and Fox, 1997). Factors such as cause of death, manner of exposure, and consumption by scavengers can

all affect the extent to which different parts of a skeleton weather (Lyman and Fox, 1997).

Behrensmeyer (1978) found that weathering stages can be used to estimate the minimum number of years since death. She maintains that her weathering stages need further testing and that the stages presented are "provisional" descriptive categories that may need elaboration and revision as additional research is conducted. Although many studies on bone weathering have been undertaken since her research, most use the weathering categories created by Behrensmeyer, and very little elaboration or revision has taken place.

Bone weathering is one of the few indicators of time-since-death available in cases involving skeletonized remains, and forensic anthropologists have occasionally used bone weathering stages and associated postmortem intervals that were never meant for application to human bones (Buchan and Anderson, 2001). As time-since-death increases, its determination becomes more subjective and the accuracy with which it can be estimated decreases (Schoenly et al., 1991; Cox et al., 1994). This study represents the first field experiment to systematically observe weathering rates in a cold climate for the purpose of developing standards for determining time-since-death in forensic contexts.

Experiments in forensic taphonomy involve the observation of processes that act on remains after death, often using animal models, and focus on identifying patterns that are comparable to those observed in recent human remains. Although many forensic field experiments have examined soft tissue decomposition (e.g. Micozzi, 1986; Schoenly et al., 1991; Anderson and VanLaerhoven, 1996; Bass, 1997; France et al., 1997; Komar

and Beattie, 1998), few have investigated the postmortem interval past skeletonization (e.g. Bass, 1997; Calce and Rogers, 2007).

For the present study, weathering stages in a cold climate were correlated with time-since-exposure for the different groups of skeletal elements of deer and pigs observed over a three year period. Weathering rates were established based on these observations and were then examined in the context of the seasonal and diurnal variations in temperature and precipitation in Edmonton, Alberta.

3.2 Materials & Methods

Materials

In this study, both deer and pigs were chosen as models for human bone weathering based on the similarities of some skeletal elements of each species with the corresponding bones in humans. Domestic pigs have been widely used as human models in forensic experiments because they have similar hairless skin and intestinal flora, are biochemically similar, and have comparably-sized thoracic cavities and fat to muscle ratios (Schoenly et al., 1991; Anderson and VanLaerhoven, 1996; France et al., 1997; Komar and Beattie, 1998). Because of their similarities in shape, the bones of deer and pigs are commonly mistaken for human bones (Ubelaker, 1978). One published study used deer to investigate scavenging and noted striking parallels between canid modification of deer carcasses and of human remains in past forensic cases (Willey and Snyder, 1989). Although deer skeletal morphology differs from that of humans, particularly in the deer's longer, thicker neck and elongated snout and metapodials, similarities were observed in the consumption sequence, carcass movement, and bone destruction of deer and human remains by canid scavengers (Willey and Snyder, 1989).

The metapodials and upper cervical vertebrae of deer are not included in this analysis as these elements have no analogues in the human skeleton.

Six pig and five deer carcasses were obtained for this experiment (see Table 3.1). Additionally, two incomplete pig skeletons from previous field experiments were also observed (see Kjorlien, 2004 and Samborski, in progress). Domestic pigs (*Sus scrofa domestica*) and both white-tailed deer (*Odocoileus virginianus*) and mule deer (*O. hemionus*) were used. Although the maximum weight for white-tailed deer is less than that of mule deer (Kreutzer 1992), there is significant overlap in the size of the limb bones of these species and they are often indistinguishable. White-tailed deer are known to attain approximately 90% of their adult bone size by 6 months of age (Purdue, 1987), and all of the deer used were estimated to be one year of age or older. Both male and female adult deer were observed for the duration of the study. Breed, sex, and age for all domestic pigs were unknown. No animals were euthanized for the purposes of this experiment; all of the pigs obtained were industry casualties, and the deer were killed in collisions or by licensed hunters. Any trauma present on the bones was obscured by scavenger gnawing. Bones were observed periodically by the author for one to three years, normally once a month or after significant thawing of snow cover.

Deer and pig carcasses were put out in each season (see Table 3.1). All carcasses were covered with staked-down chicken wire. However, this proved to be an ineffective deterrent to scavengers, since canids chewed through several layers of wire and dragged bones into the woods along animal trails where they were extensively gnawed. The bones that could be found were flagged and left in their natural position. In some cases, the majority of skeletal elements were recovered. The carcasses put out in winter were

Table 3.1. Depositional Conditions of Deer and Pigs Carcasses and Remaining Skeletal Elements

Carcass	Date of Exposure	Micro-environment	Skeletal Elements Observed
Juvenile Pig YK (previous study)	May 18, 2004	Open grassland	scapula, innominate, and some limb elements
Juvenile Pig CS (previous study)	Sept 17, 2004	Forested area	cranium and mandible
Adult Male Mule Deer	Oct 25, 2004	Forested area	limb bones, vertebral column, scapulae, and
Very Young Juvenile Pig	Nov 25, 2004	Forest margin	femur and scapula
Baby Pig	Nov 25, 2004	Forest margin	scapula
Adult Female Mule Deer (defleshed)	July 7, 2005	Forest margin	most skeletal elements, not including skull
Pig A	Jan 13, 2006	went missing	none
Pig B	Jan 13, 2006	went missing	none
Pig C	Jan 13, 2006	went missing	none
Juvenile Pig D	Jan 13, 2006	Forest margin	cranium and half of mandible
Yearling Mule Deer A	Mar 10, 2006	went missing	none
Yearling Mule Deer B	Mar 10, 2006	went missing	none
Yearling White-Tailed Deer C	Apr 18, 2006	Forested area	scapulae
Yearling White-Tailed Deer D	July 26, 2006	Open grassland	most skeletal elements, not including cranium
Subadult Pig E	Aug 2, 2006	Open grassland	most skeletal elements, not including pelvis

completely consumed or disarticulated and carried away. Several skeletal elements were observed for only part of the three year period before they were taken by scavengers (see Appendix B). Most bones had been cleaned of soft tissue by scavenger activity within a month of the carcasses being deposited. In the case of a deer put out in the summer, the desiccated hide was turned over to expose the bones underneath after one month, at which time scavengers disturbed the bones.

As a control for scavenging activity, the bones of an adult female mule deer were completely defleshed by dermestid beetles prior to being exposed. Most of the vertebral column remained articulated, and all other skeletal elements were laid out roughly in anatomical position. These bones proved to be of little nutritional interest to scavengers, allowing the effect of weathering on intact bones to be observed.

As another control for differences in micro-environment, the representative elements from most of the skeleton of a yearling white-tailed deer (D) and a subadult pig (E) were laid out next to each other in a cage after soft tissues had been removed by carnivores. This provided a direct comparison of the two species in the same open grassland habitat.

A few of the bones that were scattered by carnivores near agricultural fields were damaged by farm equipment, resulting in cut marks and crush fractures on a few of the dry bones. Some of the bones were overgrown by lush vegetation or covered completely by a thick layer of fallen leaves and, thus, could no longer be observed.

Methods

The field experiment was conducted at the University of Alberta's Experimental Farm in Ellerslie (53°25'N, 113°33'W), on the southern edge of Edmonton, Alberta. The

experimental area consists of relatively small wooded areas with open grassland and agricultural fields. The micro-environments used included open grasslands, where long grass often covered bones, marginal areas along the edge of the woods, where saplings and brush partially shaded bones, and forested areas, where fallen leaves retained moisture and thick foliage provided shade. Carcasses were exposed during different seasons to insect-mediated decomposition as well as defleshing and disarticulation by scavengers. Weathering data from the Ellerslie Research Station (compiled by Dick Puurveen, available at http://www.rr.ualberta.ca/research/Facilities/Climate/index.asp) and the nearby Edmonton International Airport (available at through Environment Canada at http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html) show average daily temperatures, amount of rainfall, and snow cover for May 2004 to June 2007 (see Appendix C). Average daily temperatures in central Alberta range from -35°C in the winter to 25°C in the summer, and significant snow cover is present for five to six months of the year. The average total rainfall over three years (2004-2006) was 340 mm.

Scavengers such as coyotes, domestic dogs, and carrion birds were observed in the area in the daytime, especially when decomposing carcasses were exposed. In addition to crows and magpies, hawks and potential scavengers such as porcupines were also directly observed in the area. Unfortunately, most of the carcasses were heavily scavenged by canids; often, only a few skeletal elements could be recovered, especially in the winter months.

On each visit to the field station, photographs were taken of each individual bone and/or carcass, and notes on their appearance were recorded. Snow cover was never disturbed, although fallen leaves covering bones were largely removed for photographs,

and then loosely replaced. Bones were disturbed only once, at the end of the observation period, when they were photographed against a black background, then returned to their original resting place. Both the upper, exposed surface and the surface contacting the ground were photographed on the final day of observation.

A biosafety protocol was established and closely followed to prevent any contamination from potential biohazards associated with pig and deer carcasses. Personal protective equipment included latex gloves, particulate respirator, and protective clothing when moving carcasses. Hands were disinfected with a 60% ethyl alcohol solution in the field and bleach was used to disinfect surfaces. Disposable gloves and waste were stored and incinerated in accordance with procedures already in place in the labs of the Anthropology Department.

Review of Forensic Case Files

In order to correlate the bone weathering stages seen in pig and deer with those of humans, the records of 14 past forensic cases from the Edmonton region were examined. An ethics proposal for this part of the study was approved by the University of Alberta's Arts, Science and Law Research Ethics Board. Also, a Proposal to Access Personal Information for Research Purposes was completed in accordance with the Freedom of Information and Protection of Privacy Act. All cases involved some degree of skeletonization and 13 had known postmortem intervals ranging from six weeks to over two years. Each bone recovered was described, and photographs or slides accompanied seven of the files.

3.3 Results

The deer and pig bone examined in this research had different characteristic weathering patterns (see Tables 3.2 and 3.3). The exposed limb bones of deer developed a single longitudinal crack within 6 to 12 months, with the majority cracking around six months. Additional cracks normally appeared between 10 and 17 months, and often after two years (see Figure 3.1). Longitudinal cracks were also seen on deer ribs between 6 and 18 months. In contrast, pig bones did not show the typical weathering characteristics described in previous research. No cracks were observed on the long bones of juvenile pigs exposed for over two years. However, rates of bone bleaching were similar for deer and pig bones.

Deer vertebrae weathered more slowly than other skeletal elements and tended to retain remnants of desiccated tissue. Weathering cracks were not observed on articular surfaces or small compact bones such as tarsals, with the exception of calcanei, which tended to develop a single longitudinal crack. Microfissures and cracks were only observed on irregular skeletal elements such as vertebrae or cranial bones in association with carnivore modification. One pig skull that was observed for nearly three years started to show separation of the cranial sutures on the exposed side of the facial skeleton.

Bones of both species in forested areas often showed only slight bleaching. Although long bones and ribs did not bleach more quickly in the grassland than in the forest, flat bones and vertebrae bleached more rapidly in the open micro-environment (see Figure 3.2). The first signs of significant bleaching were most often observed in spring and summer, however, bones exposed in an open environment in the summer months were bleached to a brilliant white by fall. The green and black staining caused by

Table 3.2. Weathering Rates for Long Bones of Deer and Pigs in Open Grassland and Forested Microenvironments

HABITAT	STAGE	DESCRIPTION		TIME SINCE EXPOSURE	
		Deer	Pigs	Deer	Pigs
Open grassland	0	Decomposition of soft tissue; brown, greasy appearance; significant periosteum remains	Soft tissue is removed; brown, greasy appearance; bones may be slightly bleached; epiphyses may remain articulated	0 - 10 months	0 - 9 months
	1	Bleaching of exposed surface; soil staining of underside; desiccated soft tissue adheres to articular surfaces; some periosteum remains; some bones remain articulated	Periods of bleaching alternating with extensive green staining; greasy appearance of ungnawed ends; epiphyses separate	10 months	9 - 23 months to 3 years
Forested area	0	Soft tissue and periosteum are removed; bones become disarticulated; slight bleaching; bone remains greasy; fungal growth	Soft tissue is removed; slight bleaching; epiphyses missing; extensive green staining; bone remains greasy where covered by leaves	0 - 13 months	0 - 17 months
	1	Single longitudinal crack; some bleaching; further disarticulation; some bone grease remains	Some bleaching; light green staining remains in patches	6 - 22 months	17 -31 months
	2	Additional cracks; soil staining of underside; remaining periosteum decays; further bleaching; complete disarticulation; some bones appear greasy	—	10 - 32 months	—

Table 3.3. Weathering Rates for Different Skeletal Elements of Deer and Pigs

BONE TYPE	STAGE	DESCRIPTION		TIME SINCE EXPOSURE	
		Deer	Pigs	Deer	Pigs
Ribs	0	Some still articulated with vertebrae; soft tissue & periosteum removed; slight bleaching; some remain greasy	Soft tissues removed; brown greasy appearance; slight bleaching & green staining	0 - 10 months	0 - 26 months
	1	Bleaching; single crack parallel to shaft; some remain slightly greasy; soil staining of underside	Periods of bleaching alternating with extensive green staining	6 - 22 to 32 months	9 - 29 months
Flat Bones (scapula, os coxa & mandible)	0	Slight bleaching; periosteum becomes desiccated and decays; some remain greasy	Bones brown & greasy; slight bleaching; some extensive green staining	0 - 24 months	0 - 23 months
	1	Some bleaching; fine cracks, orientation varies; soil staining of underside; little greasiness remains	Some bleaching; cracks extend from gnawed edges; plant growth on some bones; soil staining	3 - 32 months	9 - 36 months
Vertebrae	0	Some disarticulation & separation of epiphyses; desiccated soft tissues remain; some bones greasy; fibrous texture of some surfaces	Bones brown & greasy; some epiphyses lost; slight bleaching of epiphyseal surfaces; extensive green staining	0 - 18 months	0 - 27 months
	1	Some bleaching; more disarticulation; underside remains greasy, soil stained; some small cracks originating from gnawing	Some bleaching; separation of elements of centrum; greasiness remains if epiphysis still present on body	3 - 32 months	2 - 29 months
Calcanei	0	Periosteum removed; bone appears greasy; fungal growth	Bone remains greasy; slight bleaching; extensive green staining; loss of epiphysis	0 - 10 months	0 - 12 months
	1	Single crack on body; some disarticulation; slight bleaching; soil staining	—	6 - 32 months	—
Cranial Bones	0	Desiccated periosteum; extensive green staining	Desiccated periosteum; slight bleaching	0 - 3 months	0 - 9 months
	1	—	Some bleaching; slight greasiness; cranial sutures expanded; extensive green & brown staining	—	6 - 33 months

Figure 3.1.Deer Femur Showing Typical Longitudinal Cracking

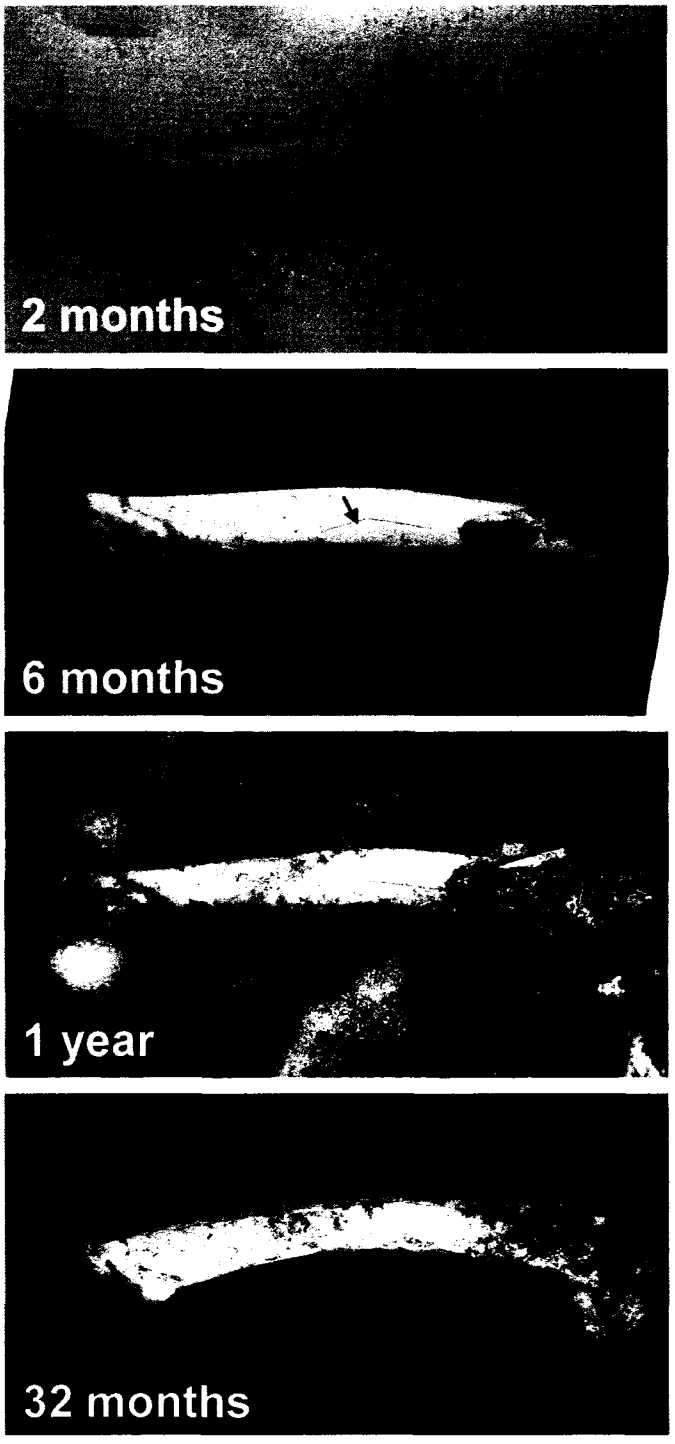
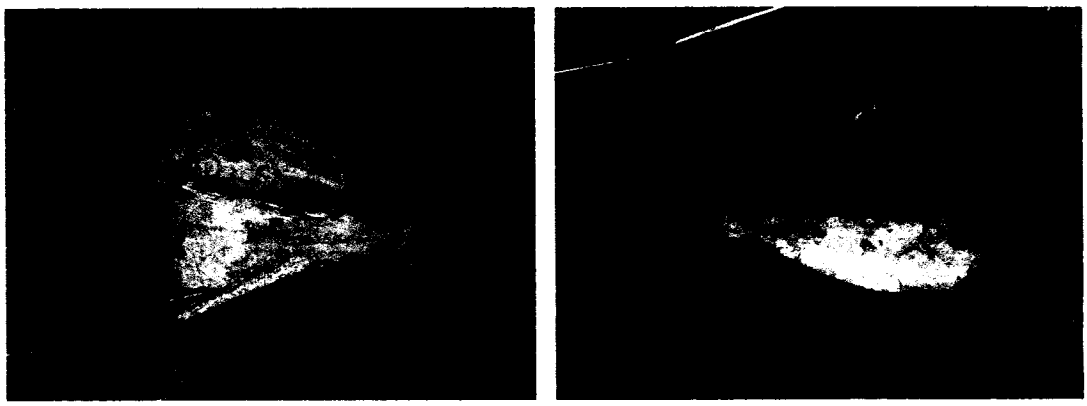


Figure 3.2. Pig Scapula in Open Grassland and Deer Scapula in Forested Micro-Environment after 2 years



algal and fungal growth after periods of wet weather obscured bleaching. Unless the bone had been repeatedly disturbed, the bone surface contacting the soil showed staining, while the exposed surface was more bleached. The exposed epiphyseal surfaces of vertebral bodies were observed to be more bleached than other parts of the bone.

Most of the bones became covered with fungus, algae, or mould during relatively wet seasons. Blackened patches of mould and extensive green staining caused by algae were common, and some of the bones showed patches of reddish or bright white fungal growth. Whereas slight green staining caused by algae often enhanced the appearance of microfissures, extensive fungal growth sometimes obscured fine cracks.

Even in relatively open areas, the presence of long grass shielded bones from direct sunlight and encouraged the growth of microfauna. After the first snowfall, the bones in open areas were covered by the flattened long grass, which insulated them against the effects of sunlight, freezing, and drying; many were again exposed after the melting of the snow cover. Similarly, fallen leaves protected bones in the forested micro-environments.

Analysis of Past Forensic Cases

A review of the records of past forensic cases in the Edmonton region revealed that, although scavenging activity was described in detail, bone weathering was very rarely mentioned, and then, only in relation to distinguishing aged animal bone from remains of forensic significance. Often, only the skull was photographed, and none of the photos or slides showed any visible signs of bone deterioration other than scavenger modification. In the field experiment, skeletal elements were gnawed in a pattern typical

of canid scavenging, replicating conditions commonly seen in past forensic cases involving human remains exposed outdoors in this region.

3.4 Discussion

The results of this experiment show that, compared to hot, arid climates (see Brain, 1967; Miller, 1975; Behrensmeyer, 1978; Gifford, 1984; Galloway et al., 1989), there is less bleaching and flaking of bone surfaces in a cold climate due to less intense exposure to sunlight. Weathering cracks are delayed compared to more arid climates, but occur more rapidly than in a rainforest or temperate climate (Tappen, 1994; Andrews, 1995), likely due to the effect of freeze-thaw cycles (see Table 3.4).

Behrensmeyer (1978) found that longitudinal cracks often appear on long bones within a few days of exposure, and bones display flaking, splitting, and splintering during the first few months of exposure. This is much more rapid than the weathering rates seen in the present study, as cracks appeared only after a few months. Gifford (1984) found that most bones are at weathering Stage 1 within six months of exposure, and by 30 to 34 months, some are at Stage 2. The findings of the present study correspond with the timing of Stage 1, but after 32 to 36 months, none of the bones have reached Stage 2. Only a single crack per bone, and sometimes slight bleaching, was typically present after the first 3 to 12 months, and no flaking or splintering was observed in a three year period. While Miller (1975) recorded transverse cracks after the second year, very few transverse cracks were observed in this experiment.

In southwest Africa, bones collected on the desert surface and in well-drained areas have chalky surfaces after several years and often have remnants of desiccated tissue adhering to them (Brain, 1967). While some elements were extensively bleached

Table 3.4. Environmental Context and Species used in Bone Weathering Studies

STUDY	LOCATION	ENVIRONMENT	TYPES OF ANIMALS	WEATHERING RATES COMPARED TO PRESENT STUDY
Brain (1967)	Southwest Africa	Desert and more humid areas	Donkey and goat	More rapid
Miller (1975)	California, US	Mountainous desert	Cattle and horses	More rapid
Behrensmeyer (1978)	Kenya, Africa	Semi-arid	Medium to large mammals	More rapid
Haynes (1981)	North-central US and Canada	Subarctic, subhumid plains	Large ungulates such as deer, moose, and bison	More rapid
Gifford (1984)	Kenya, Africa	Semi-desert	Ungulates, mostly zebra and topi	More rapid
Todd (1987)	Wyoming, US	Semi-arid continental	Bison	More rapid
Tappen (1994)	Zaire, Africa	Savanna and *rainforest*	Buffalo, elephants, monkeys, and duikers	Slower
Andrews (1995)	United Kingdom	Temperate	Cows, horses, sheep, foxes, other small mammals	Slower
Galloway et al., (1989)	Arizona	Desert and mountainous desert	Humans	More rapid
Bielenstein (1990)	Mid-eastern US	Temperate	Humans	More rapid
Bass (1997)	Tennessee	Hot and humid	Humans	More rapid

after three years, no soft tissue remained on the bones observed in the current study. Miller (1975) also observes that, after one year, two to three longitudinal cracks penetrate the compact bone and extend into the marrow cavity, and exposed patches of bone are bleached to a brilliant white. In the current study, some longitudinal cracks were seen to have deepened and widened slightly after two years, but none penetrated into the medullary cavity. Thus, weathering in the cold climate of Alberta appears to progress more slowly than the rates seen in arid climates (e.g. Brain, 1967; Miller, 1975; Behrensmeyer, 1978; Gifford, 1984). In contrast to the bone weathering patterns seen in dry African climates, cracking is delayed or absent in the rainforest environment of Zaire and bones show no bleaching (Tappen, 1994). This is contrary to the patterns seen in the present study, where cracking and bleaching occurred in both forested areas and lush grasslands.

Past studies suggest that the last skeletal elements to disarticulate, usually the vertebrae, may have greater resistance to attritional processes because articulated surfaces are protected from exposure (Hill, 1979; Gifford, 1984). Miller (1975) reports that some long bones remain articulated after four years. In contrast, Haynes (1981) notes that bones exposed in the winter separate easily when later disturbed by minor movements of animals or growing plants and that, while a small number of vertebrae can remain articulated for a year or more, they normally become separated by the end of two winters. In the present experiment, most long bones were disarticulated by 12 to 18 months, some ribs were still attached for nearly two years, three tarsals were still articulated with long bones for two and a half years, and several vertebrae were still joined by soft tissue after nearly three years despite repeated movement by scavengers. Miller (1975) observes that

small cracks are sometimes present even before the periosteum is completely removed, and this was often seen to be the case on long bones in the present study area.

In the wet, sheltered micro-environments of a temperate climate, bones become corroded at their articular ends and there is considerable loss of cancellous bone before Behrensmeyer's Stage 1 is reached (Andrews, 1995). This pattern of erosion was not seen in the subarctic micro-environments observed in this study. Andrews (1995) notes that bones in areas without vegetation become bleached, but weather much more slowly than the rates reported by Behrensmeyer, reaching Stage 1 around ten to twelve years after death; this is also slower than the weathering recorded in the present experiment, perhaps due to frequent freeze-thaw cycles in the Edmonton region.

Haynes (1980) reports that the sequence of bone deterioration in cold climates appears to be similar to that recorded by Behrensmeyer. The results of the present study support Haynes' (1981) observation that, after one year, long bones remain greasy if their epiphyseal ends have not been gnawed open. Also confirmed in this study is the contribution of moss growth to bone destruction in shaded micro-environments (Haynes, 1981); however, this was observed in very few bones, and only after one and a half to three years. Growing plant roots can widen cracks in bone, and acids secreted by the roots facilitate bone decomposition (Behrensmeyer, 1978; Haynes, 1981). Blue-green algae is considered an important agent of bone destruction in submerged finds (Grupe and Dreses-Werringloer, 1993); however, in the present study, extensive algal growth in moist, shaded subaerial contexts did not cause any visible surface deterioration of bone within three years. Slugs were invariably present on bones, likely feeding on algae, in

areas with dense vegetation during relatively wet seasons; the effects of such invertebrates on bone are unknown.

In the subarctic climate of northern Alberta, bones lying on the ground surface can be covered with snow for nearly six months, protecting them from desiccation, warming, and sunlight (Haynes, 1981). Todd (1987) notes that bones covered with snow show marked differences in dispersal and deterioration from those that remain uncovered. In a laboratory experiment, Miller (1975) found that bones develop cracks twice as fast when frozen and thawed than when they are soaked and dried. Although freezing may accelerate the cracking of bone, snow cover may actually slow the progression of weathering by insulating bones against fluctuations in temperature and humidity as well as exposure to ultraviolet light.

Haynes (1981) notes that bones lacking soft tissue dry out and begin to crack within a few hours, and that cracking is accelerated after the marrow is decomposed or consumed. This was not the case in the present study, in which most defleshed bones developed fine cracks only after three months and normally after five. Todd and colleagues (1987) found that the relatively thin, smooth cortical bone of joint surfaces tends to crack and eventually deteriorates, leaving islands of intact surface among exposed fibrous bone. The articular surfaces and compact bones observed in the current experiment did not show any signs of cracking or erosion. In the cold climate region observed by Todd and colleagues (1987), bones may take up to fifty years to reach weathering Stage 6, and hundred-year-old bison bones can be found on the surface at Stage 3. The differences observed between the results of the present research and those of other field studies in northern and central North America indicate that weathering

processes vary distinctly with micro-climate, and that taphonomic experiments need to be conducted in the specific regions in which they are being applied.

Weathering of Human Bone

Research on the weathering of human bone has been conducted using past forensic cases with known times of exposure. Galloway and colleagues (1989) conducted a retrospective study of autopsy and forensic anthropological reports from Arizona. They observed that, similar to animal bone weathering, the bleaching and exfoliation of cortical bone followed by exposure of cancellous bone and fragmentation are typical of remains found in unprotected environments. Desiccated tissue commonly remains at sites of muscle and ligament attachment and articular cartilage and intervertebral discs remain on some bone surfaces when others are showing the effects of exposure. Loss of mummified skin takes approximately eight months, then bleaching and exfoliation of the bones continues until they are extensively deteriorated. In contrast, bone remains unweathered for many years in dry, shaded areas. Their review of forensic cases indicates that human bone weathers in the same pattern as animal bone in a similar environment (Galloway et al., 1989).

In field experiments using human cadavers in Tennessee, bones start to show bleaching within the first year, typically after the first month (Bass, 1997). After the first year, bone surfaces begin to flake in moist micro-environments, and long bones develop longitudinal cracks when exposed to direct sunlight. Such cracking parallel to the shaft was also observed in deer long bones in the present study. Bass (1997) proposes that cracks occur due to rapid drying in a humid environment, and that moisture may be the most influential factor in the deterioration of bone in such climates. Although these

weathering rates seem to correspond to those reported by Behrensmeyer (1978) for the first two stages, it is unknown whether this pattern exists for the entire sequence. Comparable weathering patterns suggest that medium to large mammals, as used by Behrensmeyer (1978), would be suitable human analogues for weathering studies.

In a review of forensic cases from the mid-east United States, Bielenstein (1990) suggests that Behrensmeyer's weathering stages can be effectively applied to determine the postmortem interval in forensic contexts. The weathering stages and postmortem intervals of remains from forensic cases were compared to Behrensmeyer's stages and their associated times-since-death. None of the cases observed involved remains exposed to the environment for more than two years, so it is unclear whether bones exposed for longer would still fall within Behrensmeyer's stages. Bielenstein (1990) notes that type of clothing or covering on the body must be considered when assessing time-since-death from weathering data. This was supported in a review of forensic cases from the Edmonton region, in which clothed body parts sometimes remained completely covered with soft tissue while others were fully skeletonized.

While Behrensmeyer's stages may be applicable to forensic cases in some areas of the United States, this is likely not the case for the many different climates found across the continent. More research needs to be conducted on human remains in environments that correspond to those seen in forensic cases in North America, and weathering categories need to be developed for each skeletal element before bone weathering can be used as a reliable indicator of time-since-death (Buchan and Anderson, 2001). Because the use of human remains in forensic field experiments is highly controversial, research on bone weathering can be conducted in a variety of climates

using animal models to correlate weathering stages with time-since-death of known forensic cases in that region.

Variables Affecting Bone Weathering

Different types of bones vary greatly in the organization of their organic and inorganic components, causing bones to have differing levels of resistance to attritional forces (Singh et al., 1974; Gifford, 1981). Different skeletal elements exposed at the same time commonly exhibit varying weathering stages; for instance, small compact bones weather more slowly than other bones in the same skeleton and do not exhibit all the typical features of established weathering stages (Behrensmeyer 1978; Shipman, 1981). Unfortunately, most of the compact bones in the present experiment were removed by scavengers. Four deer tarsals appeared unweathered after nearly three years, and deer calcanei showed a single crack after 6 to 13 months. According to Gifford (1981), bones with a high surface area to volume ratio disintegrate faster than those with less exposed surface area. In this experiment, little cracking was seen on skeletal elements with proportionally greater surface area, although flat bones such as the mandible and scapula did show more advanced bleaching. It has been observed that teeth tend to weather more slowly than bone (Gifford, 1984; Phoca-Cosmetatou, 2002), and this was supported by the lack of tooth weathering seen in this experiment. Black stains on the teeth used in the current study were bleached away and slight green staining from algal growth sometimes appeared, but no cracking was observed.

Structural variation in the bones of different species also affects weathering rates. The bones of similarly-sized mammals from different species have been observed to weather at different rates due to anatomical differences (Hill 1975; Gifford, 1981).

Juveniles are underrepresented in the later weathering stages compared to small adult animals, indicating that immature bone structure may be a more significant factor than size in weathering rates (Behrensmeyer, 1978). The juvenile pig bones in this study did not weather in the same pattern as the deer bones. Although the bones of both species became bleached, none of the immature pig long bones cracked in two and a half years of exposure. This suggests that immature pig skeletons may not be suitable as human analogues in bone weathering experiments. Because all of the pig long bones used in this study had epiphyses that were unfused or only partly fused, comparisons with adult deer long bones are problematic. However, the direct comparison of a subadult pig (E) with a yearling deer (D) reveals that both sets of long bones were uncracked after ten months, thus age may be a more important factor than species in bone weathering. It was difficult to distinguish surface deterioration from the normal fibrous texture of juvenile bone.

Even small-scale variations in micro-environment can alter the progression of bone weathering. Different parts of a single bone can weather at different rates, with the upper, exposed surface of a bone typically being more weathered than the subaerial surface (Behrensmeyer, 1978; Gifford, 1981; Bielenstein, 1990). This was confirmed in the present study in bones that had not been repeatedly disturbed by scavengers. Movement through weathering stages is slowed when bones are protected from sunlight and humidity fluctuations by dense vegetation (Hill 1975; Behrensmeyer, 1978; Haynes, 1981; Tappen, 1994). In the present study, bones that were deposited where grass had been mowed became bleached much more quickly than bones in lush grasslands or forested areas, although they had not developed any cracks within ten months. The shade

and moisture provided by trees, fallen leaves, and long grass protected the bones in both wooded areas and grasslands from bleaching.

The slower weathering rates found in humid habitats indicate that drying plays an important role in the cracking of bone (Tappen, 1994). Many cracks developed in the present experiment following periods of 8 to 12 days of dry weather in the spring, late summer, or fall. Very humid conditions sometimes caused fissures to narrow, making cracks less visible. Thus, although cracks tend to deepen over time, this process may be reversed if the bone stays wet. Dry bone retaining some collagen starts to exfoliate and splinter when exposed to periods of dry warmth (Haynes, 1981). Over the past 3 years, 10 to 20 consecutive dry days with average temperatures between 15 and 20°C were occasionally seen during the summer months, but were not common (see Appendix C).

When correlating weathering stages to postmortem intervals, Behrensmeyer uses the assumption that the maximally weathered bone of a carcass was exposed immediately after death, even though exposure duration is invariably less than time-since-death (Lyman and Fox, 1997). During the winter months in the Edmonton region, it was observed that a pig carcass could be completely devoured by canid scavengers in as little as nine days, while in the summer, hide sometimes became mummified and prevented bones from being exposed. Some bones were disturbed or removed long after any food value remained, likely due to the activity of domestic dogs in the surrounding area. All bones were exposed within a month of the carcass being deposited. When carcasses were put out in spring and summer months, scavengers did not destroy wire enclosures to consume soft tissues, so bones were exposed artificially in two cases. In one case, the deer was completely defleshed by dermestid beetles, and in another, the desiccated hide

was reflected to expose the bones underneath. Because the results of this study present weathering rates for exposed bones, the decomposition rates for a body deposited in a given season in the Edmonton region must be taken into account when applying these weathering stages to forensic cases.

Applications

Behrensmeyer's weathering stages and corresponding postmortem intervals have been used by forensic investigators to estimate the time-since-death of skeletonized human remains, usually to establish whether bones have been exposed for less than three years (Buchan & Anderson 2001). According to Ubelaker (1997), taphonomic models developed in palaeontology, such as that created by Behrensmeyer, have direct utility in forensic anthropology in estimating the postmortem interval, reconstructing the depositional environment, and distinguishing perimortem trauma from taphonomic factors. However, Buchan and Anderson (2001) caution that Behrensmeyer's research on bone weathering may not be applicable to forensic cases, since her stages were developed based on observations of large mammals in Africa.

There are several applications of bone weathering stages beyond their use in forensic anthropology. Information gained from modern forensic cases can contribute to palaeoanthropological interpretations of taphonomic and cultural modifications of ancient hominid remains (Ubelaker, 1991). Knowledge about weathering patterns can be used in archaezoology to determine whether taphonomic processes are obscuring evidence of past human behavioural modification of bone assemblages (Phoca-Cosmetatou, 2002). Weathering can also provide important archaeological information on the relative

duration of occupation, the recurring use of a site, or the presence of non-cultural bone material (Behrensmeyer, 1978).

Although bone weathering rates are influenced by several variables, the general sequence of change is relatively stable and provides a standardized way of assessing weathering, which is important in interpreting the depositional environment and postmortem interval (Buikstra and Ubelaker, 1994). Grisbaum and Ubelaker (2001) identify a need for more complete record keeping in order to properly assess taphonomic factors and the postmortem interval in forensic cases. Developments in the study of forensic taphonomy and the growing standardization of techniques used in anthropological analysis have led to an increase in descriptive documentation of forensic cases in the United States. Information on bone weathering needs to be included in such documentation to fully reconstruct postmortem conditions. Bone weathering patterns can be used to identify taphonomic events such as movement of remains after skeletonization, as the surface contacting the soil will be stained and the exposed surface more bleached. Discoloration by fungal growth and the absence of bleaching can indicate that the bone was exposed in a moist area with dense vegetation for at least one spring/summer season.

It is important for medicolegal investigators to be familiar with bone weathering cracks so that they can be distinguished from perimortem trauma. Calce and Rogers (2007) showed that blunt force trauma can be obscured by weathering effects. In a review of the records from past forensic cases showing advanced decomposition in the Edmonton region, it was observed that, although scavenging activity was described in detail, bone weathering was very rarely mentioned, and then, only in relation to distinguishing aged animal bone from remains of forensic significance. Even if time-

since-death is already known, the recording of weathering characteristics could later form the basis for correlation of weathering stage with time-since-death in different climates.

Future Research

Unfortunately, all of the pigs used in this experiment were juvenile, making comparisons with adult and sub-adult deer somewhat problematic. The results of this experiment suggest that bone weathering patterns vary significantly with age and/or species; therefore, immature pig skeletons may not be suitable as human analogues for bone weathering experiments. More research is needed to determine whether juvenile pigs may be appropriate models for immature human bones.

This preliminary study could be expanded with a larger sample of animals of different ages and a greater variety of different micro-environments. Also, different species, such as bear, dog, or sheep could be tested to further investigate the best animal model for human bone modification.

Comparisons of animal models to forensic cases from the region with associated postmortem intervals are needed to correlate the weathering rates observed in deer skeletons with those seen in human remains. In a review of fourteen forensic cases involving skeletonized remains in the Edmonton region, none had known times of exposure as well as documentation or clear photographs of bone weathering. Records of past forensic cases in other areas of Alberta need to be examined.

3.5 Conclusion

This research adds to the limited body of knowledge on weathering in a cold climate and will increase the precision with which weathering stages can be used to assign time-since-death in local forensic cases. The large seasonal temperature

fluctuations in central Alberta and the significant snow cover present for approximately five months of the year contribute to the weathering patterns observed in this experiment.

In the first weathering stage seen in this study, deer long bones consistently develop a single longitudinal crack. This pattern is very similar to that described by Bass (1997) for human long bones, suggesting that deer skeletons may be ideal human analogues for bone weathering experiments. However, the present research still needs to be correlated with weathering rates for human bones from past forensic cases in this area. Despite the densitometric and geometric similarities between the compact bone of humans and pig, the bones of these species weather quite differently. Therefore, juvenile pigs are not suitable models for forensic experiments observing taphonomic processes acting on the skeleton.

After nearly three years, no clear flaking was observed, there was moderate bleaching on most bones, and cortical surfaces remained intact, with no chalkiness or erosion. The growth of algae, mould, and fungus on damp bones often obscured bleaching; thus, this weathering characteristic cannot be reliably associated with time-since-death in moist micro-environments. Thus far, the patterns observed support the conclusion that bone weathering in a cold climate proceeds more slowly than established stages based on experiments in hot, arid climates and more rapidly than those in temperate or rainforest environments.

The postmortem interval is notoriously difficult to determine after soft tissues have decomposed, and bone weathering patterns can be a valuable tool for reconstructing postmortem events. However, weathering experiments using animal models need to be

conducted in other areas before bone weathering can be used to establish time-since-death for skeletal remains recovered in different climates.

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4. 4. Conclusions & Future Research

4.1 Conclusions

The present study aimed to find a suitable human analogue for a field experiment investigating bone weathering rates in a cold climate. The purpose was to establish weathering stages for application to the determination of time-since-death in forensic cases with extended postmortem intervals.

The first part of this study involved the measurement and comparison of the cortical properties of the long bones of deer, pigs, and humans. This research represents the only interspecies comparison of bone properties aimed at justifying the use of animal models in forensic experiments using skeletal remains. The results imply that both deer and pig skeletons have some geometric and densitometric similarities to human bone. Cortical bone density was variable among different species; the femur and humerus of deer were more similar to those of humans, while the tibia and radius of pigs were closer to the corresponding human bones. Cortical thickness and area showed no clear pattern of variability between human, pig, and deer bone. Although the length of deer long bones is more similar to that of human bones, more research is needed on adult pig bones of different sizes. The findings of this study can be of use in designing forensic experiments using animal models to investigate bone modification caused by scavenging or trauma.

The results of the first part of the study were applied to a taphonomic experiment on bone weathering using human analogues. The field experiment aimed to contribute to the limited body of knowledge on weathering in a cold climate. The extreme temperature ranges in central Alberta and the significant snow cover present for nearly half the year influenced the weathering patterns observed in this experiment. A single longitudinal

crack developed on deer long bones between six months and one year after exposure. After nearly three years, no flaking or surface erosion was observed, and there was moderate bleaching on most bones. The patterns observed support the conclusion that bone weathering in a cold climate proceeds more slowly than established stages based on experiments in hot, arid climates and more rapidly than those in temperate or rainforest environments. Weathering stages and associated postmortem intervals were established for specific skeletal elements and different micro-environments, thereby increasing the precision with which weathering stages can be used to assign time-since-death.

The results of the field study suggest that deer skeletons are ideal human analogues for bone weathering and scavenging experiments. Despite the densitometric and geometric similarities between the compact bone of humans and pigs, the bones of these species weather quite differently. Therefore, juvenile pigs are not suitable models for forensic experiments observing taphonomic processes acting on the skeleton.

There are very few methods for determining time-since-death after soft tissues have decomposed, and these are highly subjective. Bone weathering patterns can be a valuable tool for reconstructing the depositional environment and postmortem events in forensic contexts. However, weathering experiments using animal models need to be conducted in other areas before bone weathering can be used to establish time-since-death for skeletal remains recovered in different climates.

Applications

Behrensmeyer's (1978) weathering stages and corresponding postmortem intervals have been used by some forensic anthropologists to determine the time-since-death of skeletonized human remains. However, her stages were developed based on

observations of large African mammals and may not be applicable to human bones or in other climates (Buchan and Anderson, 2001).

Bone weathering needs to be assessed in forensic investigations for the full reconstruction of postmortem events. Differential bone weathering patterns can be used to analyze the season and environmental conditions of deposition as well as the movement of remains after skeletonization. It is important for medicolegal investigators to be familiar with the appearance of bone weathering cracks so that they can be distinguished from perimortem trauma. In a review past forensic cases showing advanced decomposition, it was observed that scavenging activity was recorded in detail while bone weathering was rarely mentioned.

There are several applications of bone weathering stages beyond their use in forensic anthropology. Information gained from modern forensic cases can contribute to palaeontological and zooarchaeological interpretations of taphonomic and cultural modifications of faunal remains (Ubelaker, 1991; Phoca-Cosmetatou, 2002). Weathering can also provide important archaeological information on the relative duration of occupation and repeated use of a site (Behrensmeyer, 1978).

4.2 Future Research

The only pigs available for this experiment were juvenile, making comparisons with adult deer and humans somewhat problematic. Weathering cracks were not observed on the bones of juvenile pigs, even after more than three years of exposure. This suggests that bone weathering patterns vary significantly with age and/or species; therefore, immature pig skeletons are not be suitable as human analogues for bone weathering

experiments. However, more research is needed to determine whether juvenile pigs may be appropriate models for immature human bones.

The field experiment could be elaborated with a larger sample of animals of different ages and a greater variety of different micro-environments. Also, different species such as bear, dog, or sheep could be tested to further investigate the best animal model for human bone modification.

Comparisons of the animal models used in this study to human remains in forensic cases are needed to correlate the weathering rates observed in deer skeletons with those seen in human remains. A review of forensic case files from central Alberta turned up no records with known times of exposure as well as documentation or photographs of bone weathering. The records of forensic cases with extended postmortem intervals from surrounding regions need to be examined. Once the stages developed in this study are correlated with weathering rates for human bones, they can be applied in forensic contexts to determine time-since-death for skeletonized remains in cold climates. Similar field experiments can also be conducted to correlate weathering stages with time-since-death in different climates.

4.3 References

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Appendix A. Cross-Sectional Measurements (mm) of the Cortical Properties of Human, Pig, and Deer Bone

	Bone	Section	Total Cross-Sectional Area (TA)	Cortical Area (CA)	CA/TA *100	Length	Maximum Medio-Lateral Diameter (MLD)	CA/MLD	ML Combined Cortical Thickness (CCT)	Antero-Posterior CCT	Cortical Density (g/mL)
Human	Femur	Proximal	596.8	384.9	64.9		27.7	13.9	13.0	12.7	1.9
		Midshaft	555.2	374.0	67.5	462.2	27.3	13.7	14.2	12.7	1.9
		Distal	577.3	333.8	58.4		27.9	12.0	11.3	10.3	1.6
		All	574.6	365.1	63.9		27.6	13.2	13.0	12.0	1.8
	Tibia	Proximal	520.0	318.7	61.5		23.8	13.4	7.2	13.3	1.9
		Midshaft	413.0	296.6	71.7	376.7	21.4	13.8	8.4	13.8	2.2
		Distal	349.1	252.9	72.4		21.8	11.6	8.9	11.1	2.2
		All	426.2	290.1	68.8		22.2	13.0	8.2	12.8	2.1
	Humerus	Proximal	332.2	165.9	49.9		20.5	8.0	6.2	7.3	1.5
		Midshaft	307.6	175.2	56.9	331.9	20.6	8.5	7.5	7.8	1.6
		Distal	280.7	170.7	60.3		18.8	9.0	7.3	8.5	1.8
		All	306.9	171.0	55.8		20.0	8.5	7.1	7.8	1.6
	Radius	Proximal	124.6	88.5	71.3		15.3	5.8	6.9	5.2	2.0
		Midshaft	110.3	88.5	80.4	242.7	15.0	5.9	6.9	6.3	2.5
		Distal	109.3	81.9	75.0		13.9	5.9	6.2	5.7	2.2
		All	114.3	86.5	76.0		14.7	5.8	6.7	5.8	2.2

	Bone	Section	Total Cross-Sectional Area (TA)	Cortical Area (CA)	CA/TA *100	Length	Maximum Medio-Lateral Diameter (MLD)	CA/MLD	ML Combined Cortical Thickness (CCT)	Antero-Posterior CCT	Cortical Density (g/mL)
Pig	Femur	Midshaft	294.9	183.4	63.4		18.9	9.7	7.3	8.5	1.8
		All	334.8	189.8	59.1	157.5	20.1	9.5	7.1	8.2	1.9
	Tibia	Midshaft	218.6	154.0	70.7		18.8	8.2	9.1	6.6	1.7
		All	243.5	155.2	65.8		19.2	8.1	8.2	6.9	1.7
	Humerus	Midshaft	258.3	187.7	73.1		20.4	9.2	10.6	8.4	2.1
		All	268.9	188.6	71.5		20.9	9.1	10.7	7.9	1.9
	Radius	Midshaft	139.8	110.4	78.9		16.4	6.7	9.6	5.4	1.7
		All	153.6	107.4	71.0		16.9	6.4	8.5	5.0	1.6

	Bone	Section	Total Cross-Sectional Area (TA)	Cortical Area (CA)	CA/TA *100	Length	Maximum Medio-Lateral Diameter (MLD)	CA/MLD	ML Combined Cortical Thickness (CCT)	Antero-Posterior CCT	Cortical Density (g/mL)
Deer	Femur	Proximal	397.1	188.7	48.4		21.7	8.7	5.6	6.8	2.0
		Midshaft	308.9	168.3	54.9	238.8	19.1	8.8	6.2	6.3	2.0
		Distal	438.5	216.9	49.8		23.3	9.3	7.3	6.9	2.2
		All	363.3	185.5	52.0		20.8	8.9	6.3	6.6	2.0
	Tibia	Proximal	438.2	279.8	63.4		23.8	11.6	7.7	8.4	2.2
		Midshaft	309.6	220.0	70.9	267.0	20.9	10.4	9.1	8.4	2.0
		Distal	296.3	207.0	69.4		21.2	9.7	9.1	7.9	2.0
		All	338.4	231.7	68.7		21.7	10.5	8.7	8.3	2.0
	Humerus	Proximal	473.7	236.7	50.2		27.8	8.5	9.0	5.9	2.0
		Midshaft	323.9	180.2	55.8	183.0	21.9	8.1	7.1	6.5	2.1
		Distal	326.2	201.4	60.9		21.3	9.3	8.4	7.1	2.5
		All	361.9	199.6	55.7		23.2	8.5	7.9	6.5	2.2
	Radius	Proximal	208.1	161.2	77.8		22.0	7.3	9.8	6.3	1.9
		Midshaft	196.1	154.2	78.8	206.0	20.2	7.6	9.3	6.8	2.1
		Distal	227.9	157.8	68.8		20.9	7.5	8.7	5.8	2.5
		All	207.1	156.9	76.0		20.8	7.5	9.3	6.4	2.1

Appendix B. Bone Weathering Observations

Carcass	Date of Exposure	Season	Micro-environment	Long Bones: 1st Longitudinal Crack	Long Bones: Additional Cracks	Long Bones: Bleaching
[redacted]	[redacted]	late spring	open grassland			04.25.05 - 04.23.06 11-23 months
Juvenile Pig CS	09/17/04	early fall	forested area			
Young Juvenile Pig (burnt)	11/25/04	late fall	margin of forest			04.23.06 17 months
Baby Pig	11/25/04	late fall	margin of forest			
Pig D	01/13/06	winter	margin & forest			
[redacted]	[redacted]	late summer	open grassland mowed			05.17.07 9 months
Adult Male Mule Deer	10/25/04	fall	forested area	04.25.05 - 10.27.05 6 -12 months	09.17.05 - 06.30.07 11 -32 months	04.25.05 - 08.09.06 6 -22 months
Adult Female Mule Deer (defleshed)	07/10/2005*	winter/summer	margin & forest	09.17.05 - 12.13.05 6 - 9 months	01.29.06 - 08.09.06 10 -17 months	04.08.06 - 10.22.06 13-19 months
Yearling White-tailed Deer C	04/18/06	spring	forested area			
[redacted]	[redacted]	summer	open grassland mowed			05.17.07 - 10 months

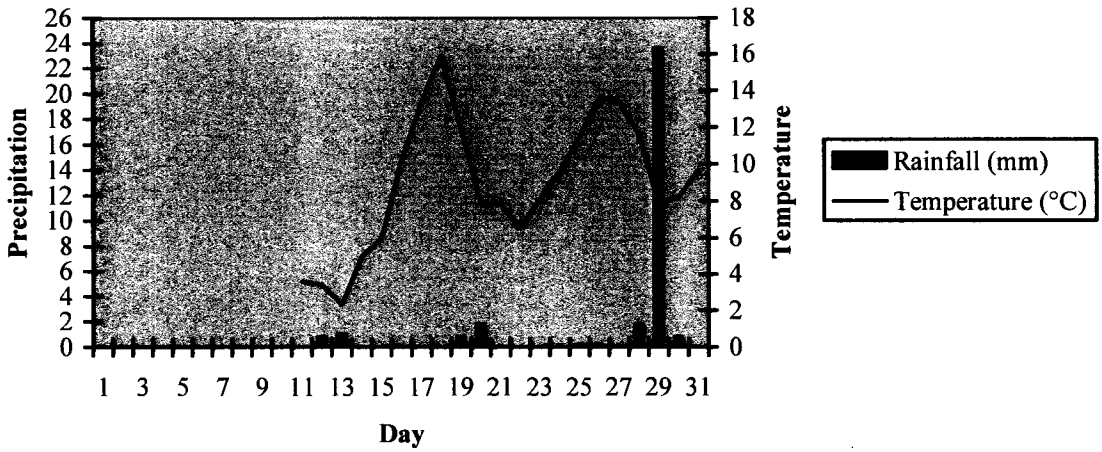
* Bones exposed outdoors from 11/29 to 03/29/2004, then placed indoors with dermestid beetles.

	Ribs		Scapulae		Innominates	
Carcass	**Cracking**	**Bleaching**	**First Crack**	**Bleaching**	**Cracking**	**Bleaching**
[redacted]		[redacted]	[redacted]	[redacted]		[redacted]
Young Juvenile Pig (burnt)			no change 06.30.07 9 months	31 months no change 10.22.06 23 months		
Baby Pig						
[redacted]		[redacted]		[redacted]		
Adult Male Mule Deer	09.17.05 - 08.09.06 11-22 months	05.12.05 - 04.08.06 7 - 18 months	06.30.07 32 months		06.26.06 20 months	06.30.07 32 months
Adult Female Mule Deer (defleshed)	09.17.05 - 08.09.06 6-17 months	08.09.06 - 05.01.07 17 - 19 months	09.17.05 - 08.09.06 6 -17 months		04.08.06 13 months	
Yearling White-tailed Deer C				05.01.07 13 months		
[redacted]		[redacted]		[redacted]		

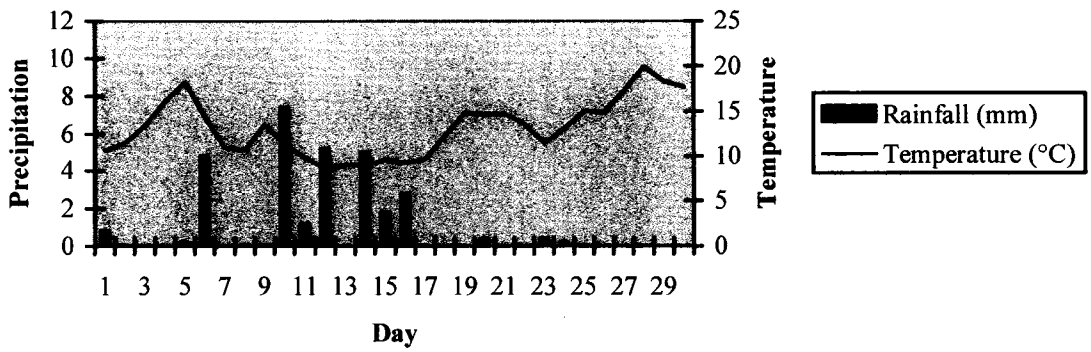
Carcass	Vertebrae Bleaching	Crania Cracking	Crania Bleaching	Mandibles Cracking	Mandibles Bleaching	Calcanei Cracking
[redacted]					04.25.05 11 months	no change 05.18.06 12 months
Juvenile Pig CS		05.12.05 8 months	04.23.06 19 months	04.23.06 19 months	04.23.06 19 months	
Pig D			07.26.06 6 months	10.22.06 9 months	10.22.06 9 months	
[redacted]			05.17.07 9 months		05.17.07 9 months	
Adult Male Mule Deer	04.08.06 - 08.09.06 18 - 22 months	no change 01.22.06 3 months				04.25.05 6 months
Adult Female Mule Deer (defleshed)	08.09.06 - 06.30.07 17-27 months					01.29.06 10 months
[redacted]				05.17.07 10 months	10.22.07 3 months	

Appendix C. Weather Data for Ellerslie Research Station and Surrounding Areas

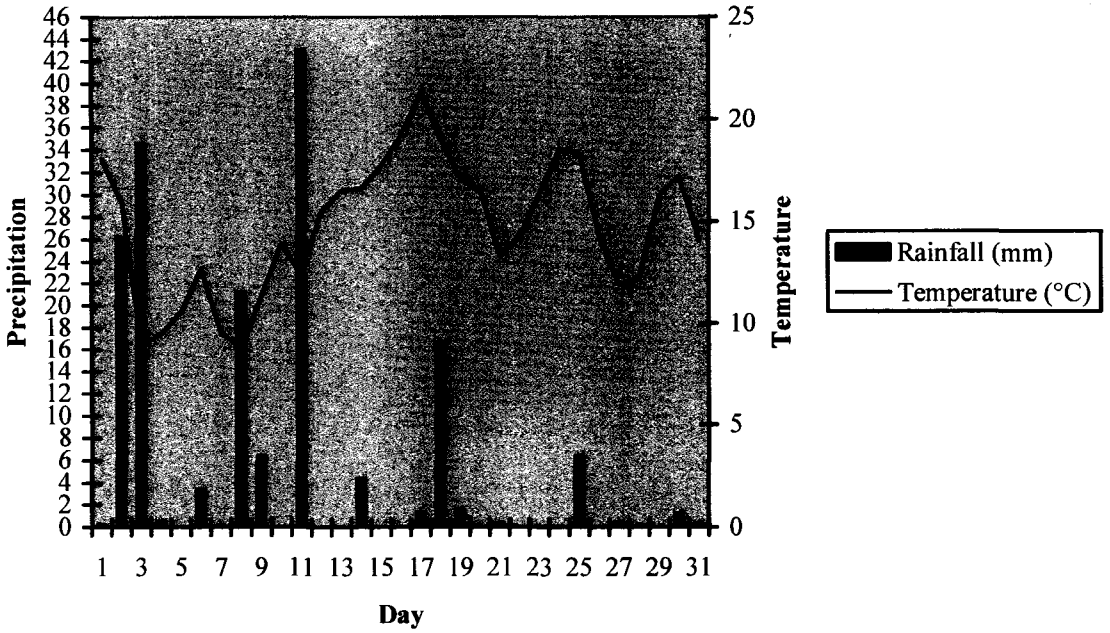
Average Daily Temperature and Precipitation for May 2004



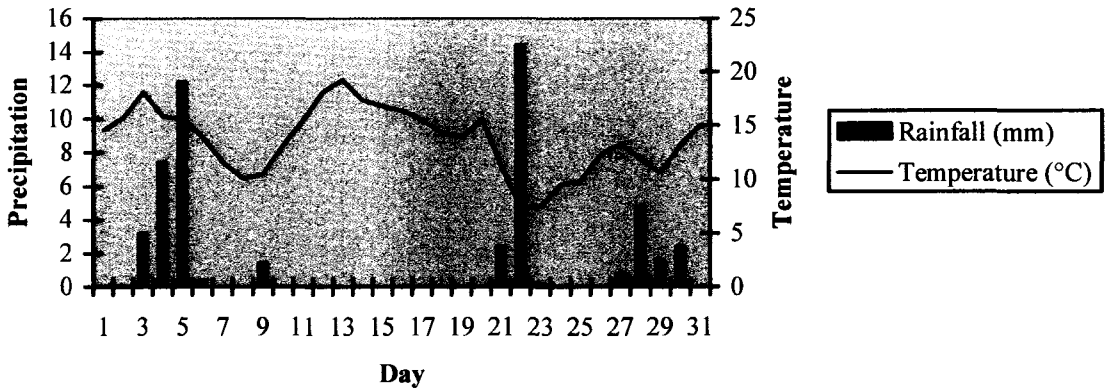
Average Daily Temperature and Precipitation for June 2004



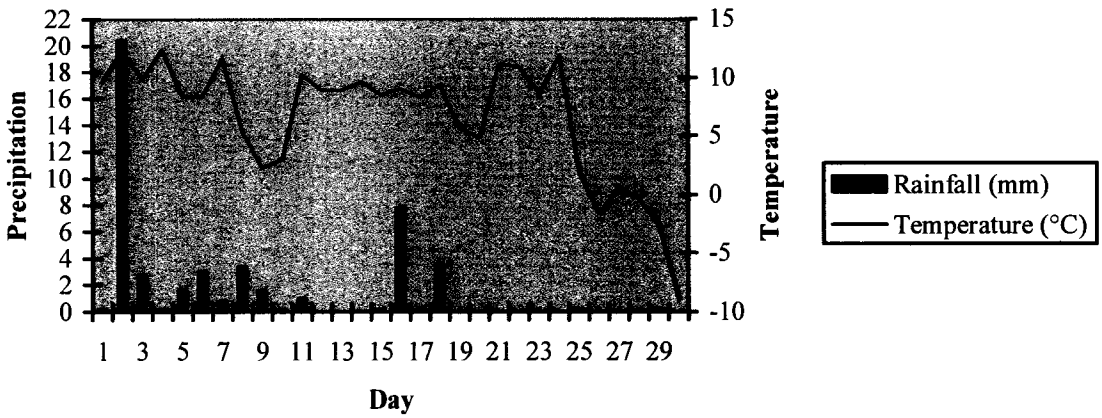
Average Daily Temperature and Precipitation for July 2004



Average Daily Temperature and Precipitation for August 2004

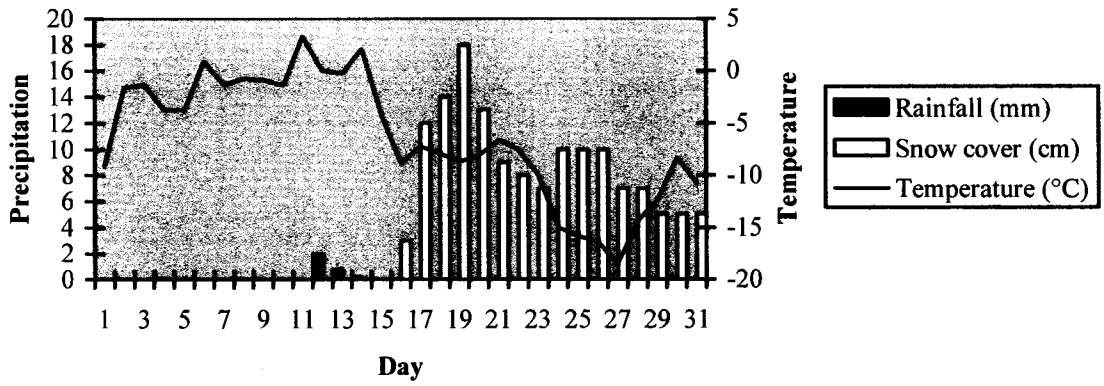


Average Daily Temperature and Precipitation for September 2004



* Data for Ellerslie Research Station not available, purple line represents data from the Edmonton International Airport approximately 20 km away.

Average Daily Temperature and Precipitation for October 2004



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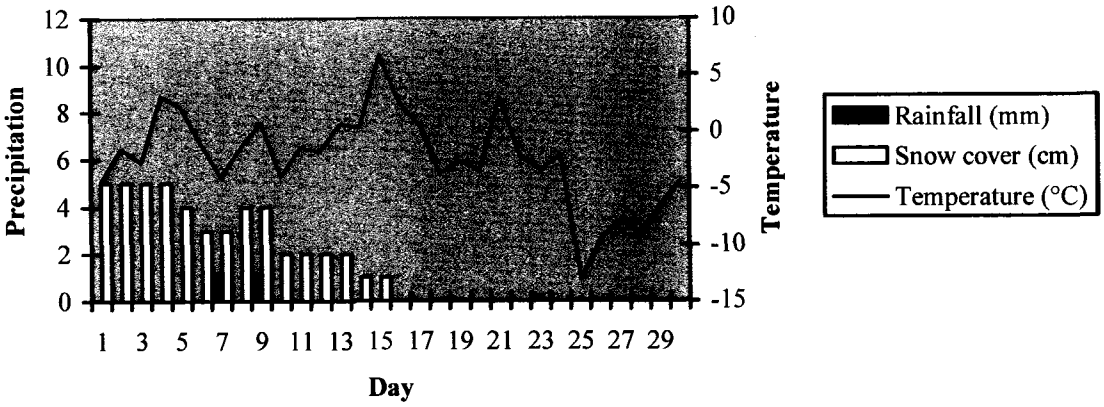

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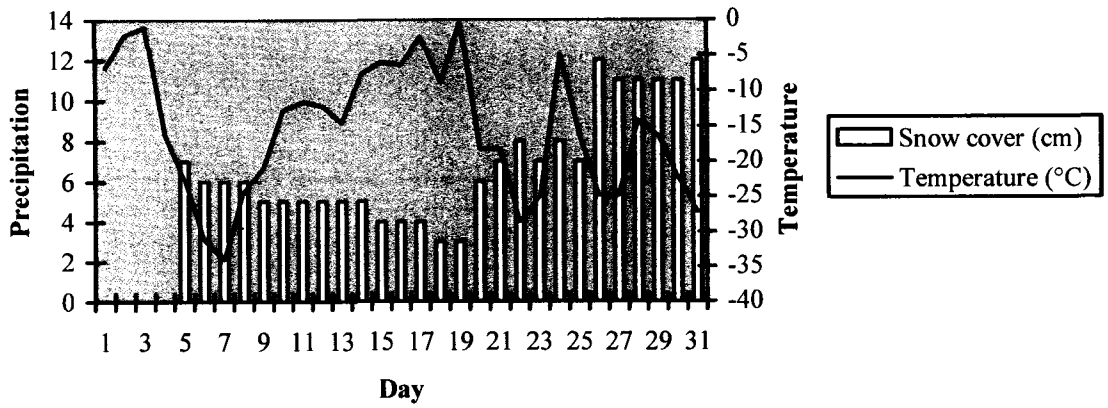

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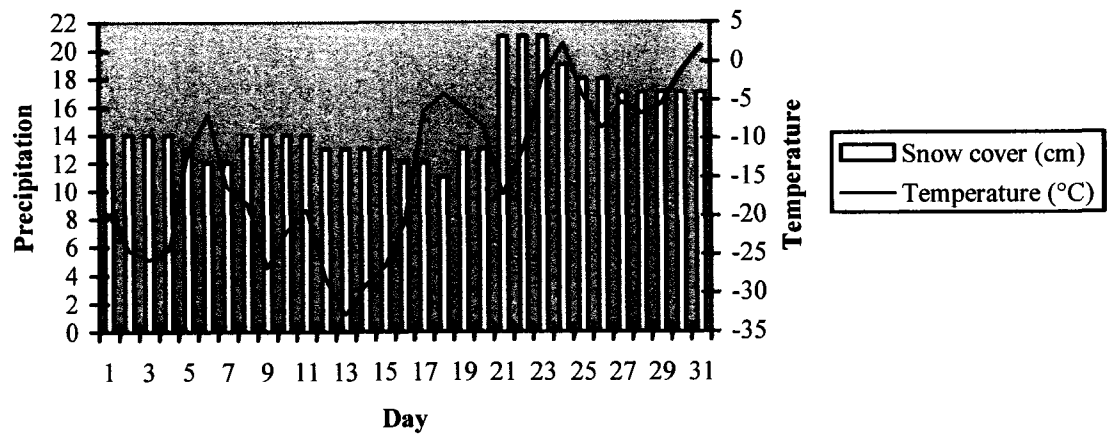

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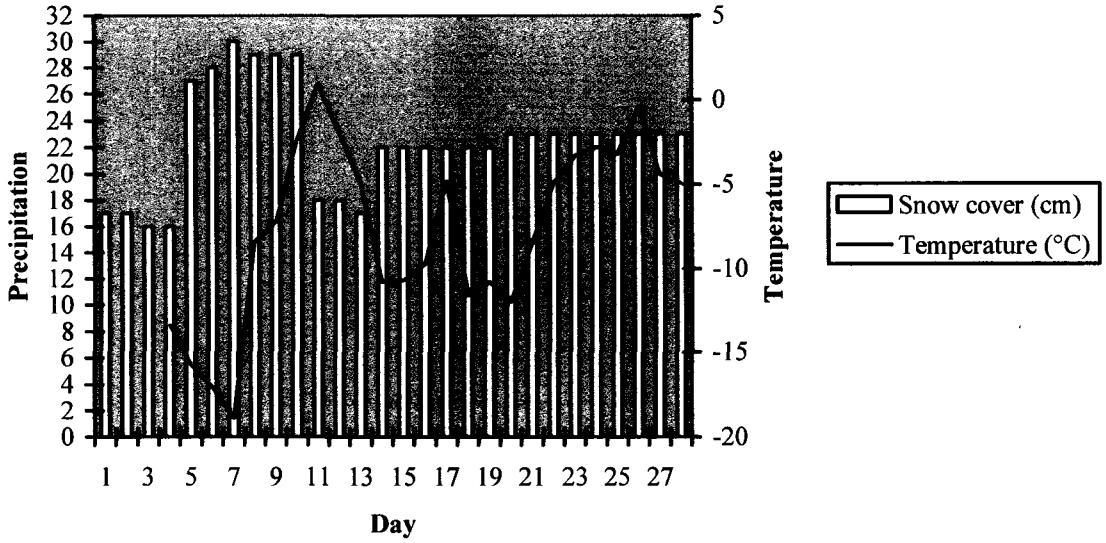

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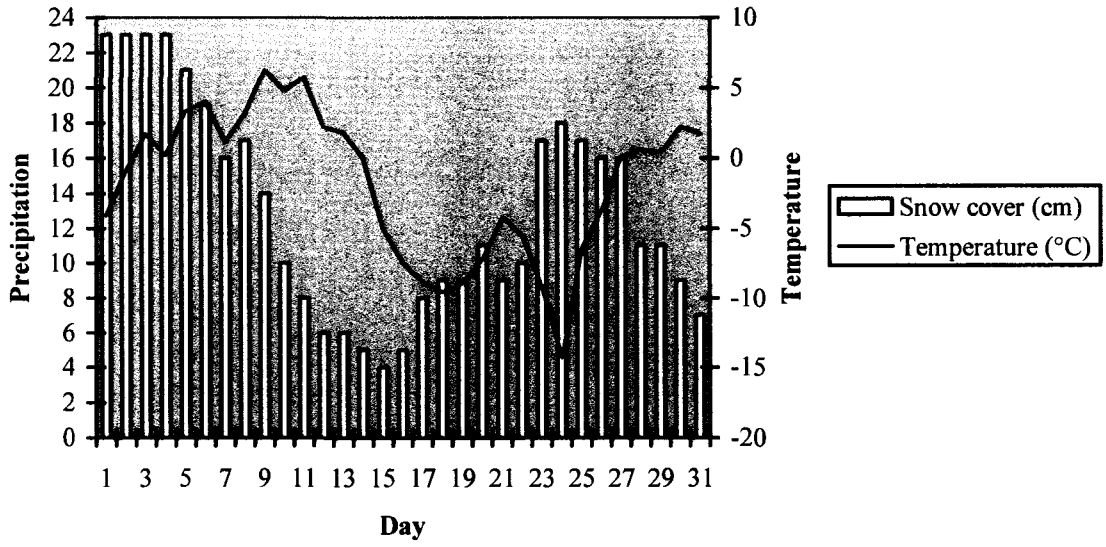
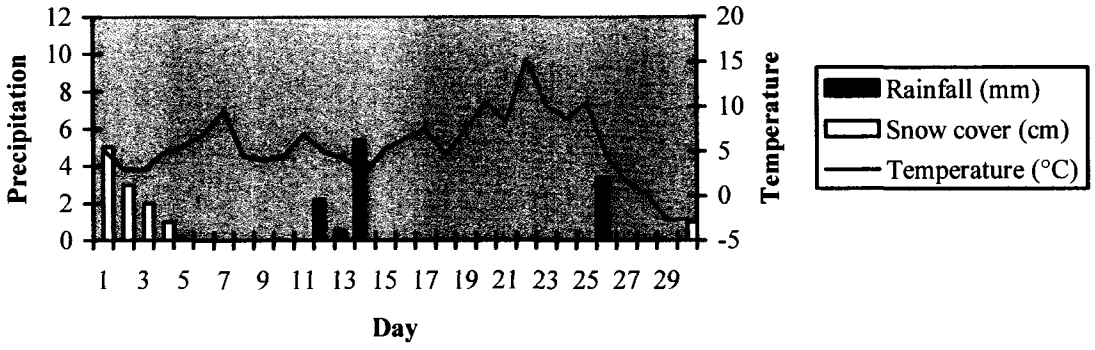


Average Daily Temperature and Precipitation for April 2005



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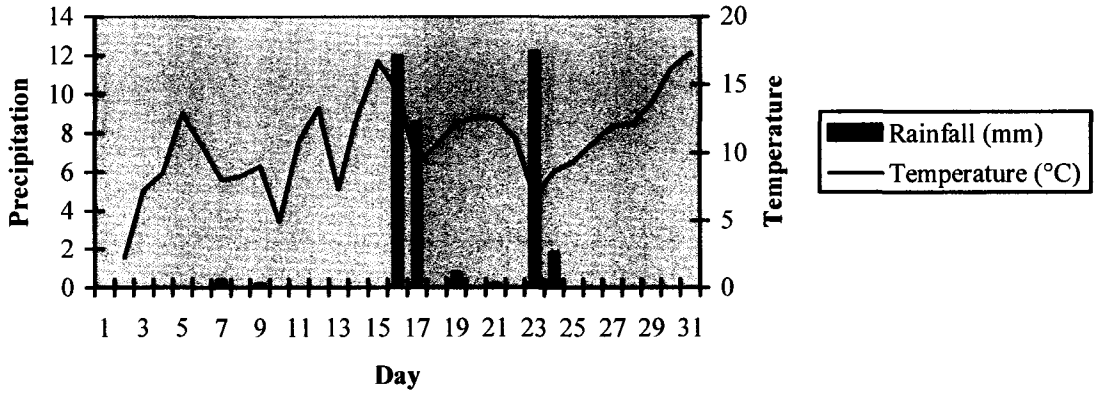

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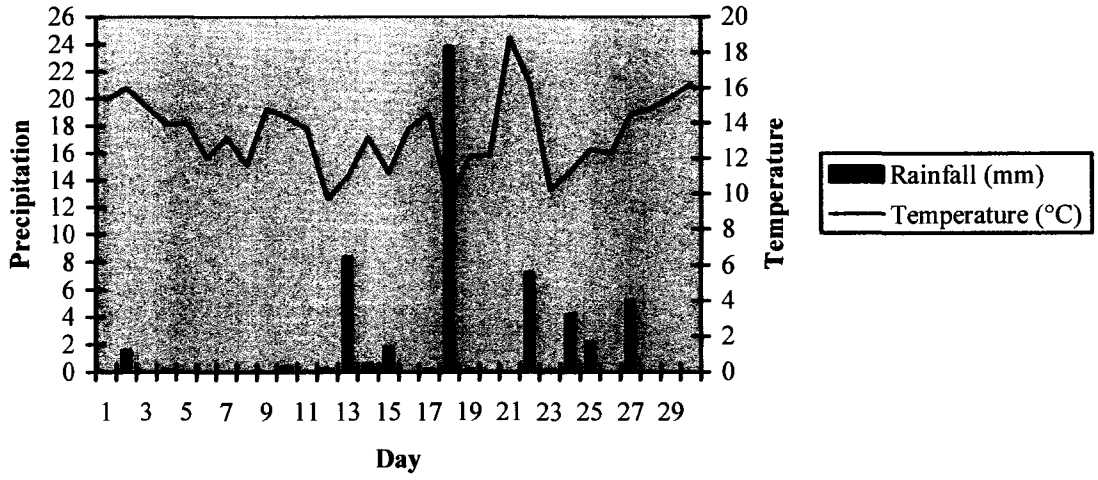

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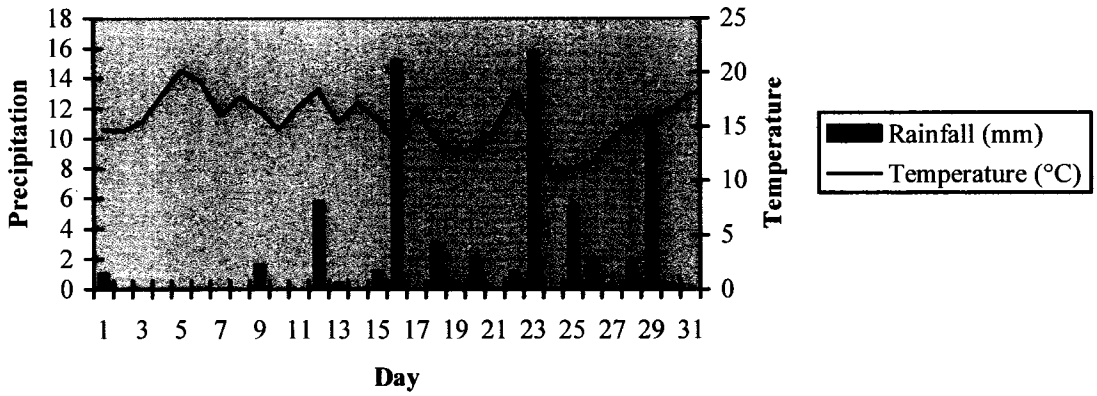

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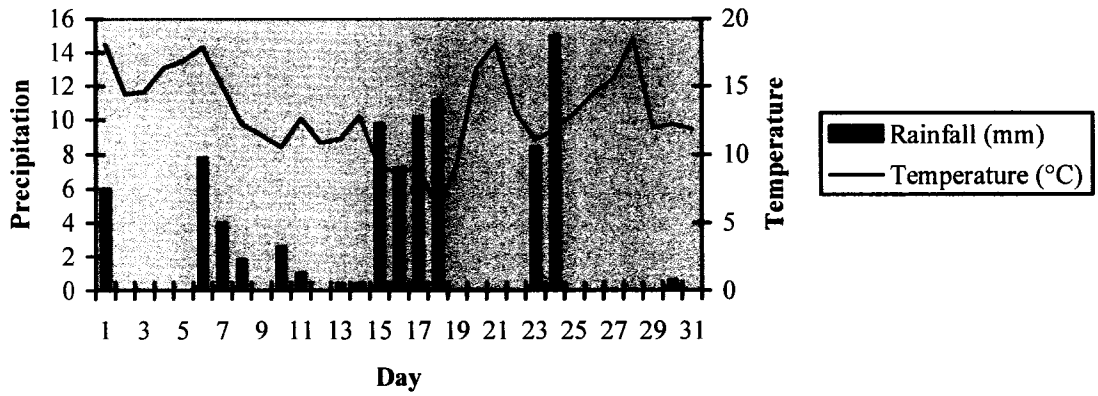
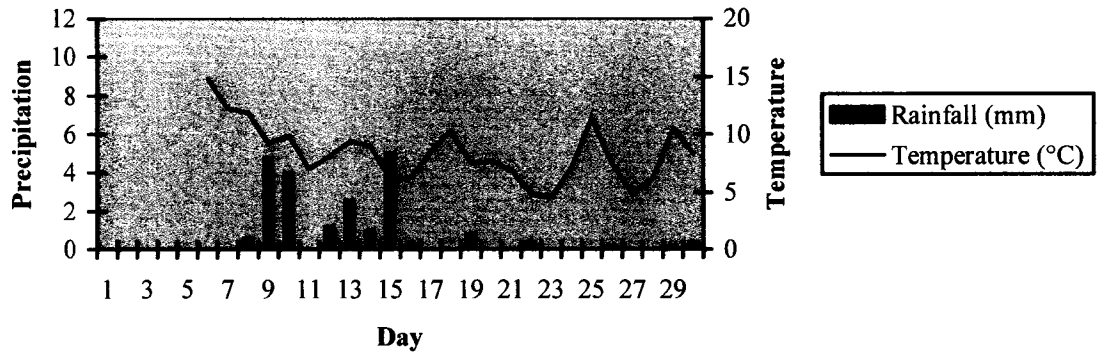


Average Daily Temperature and Precipitation for September 2005



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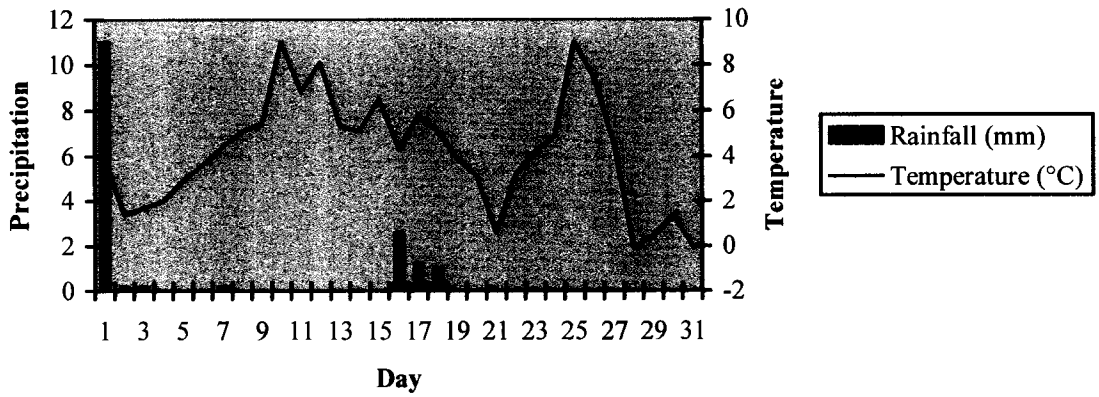

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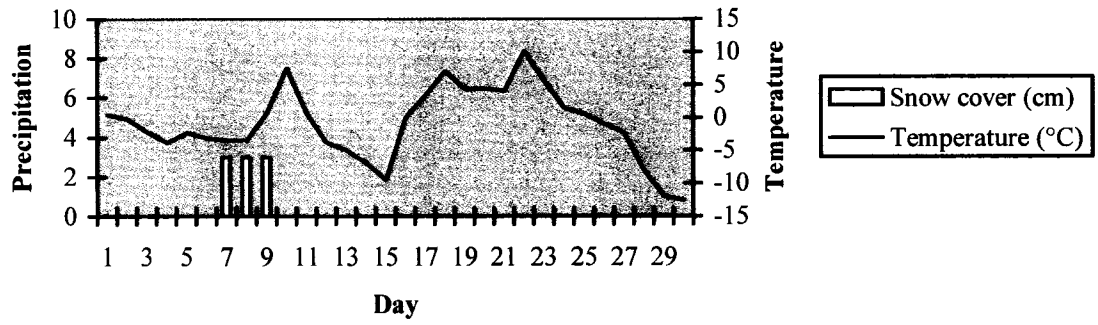

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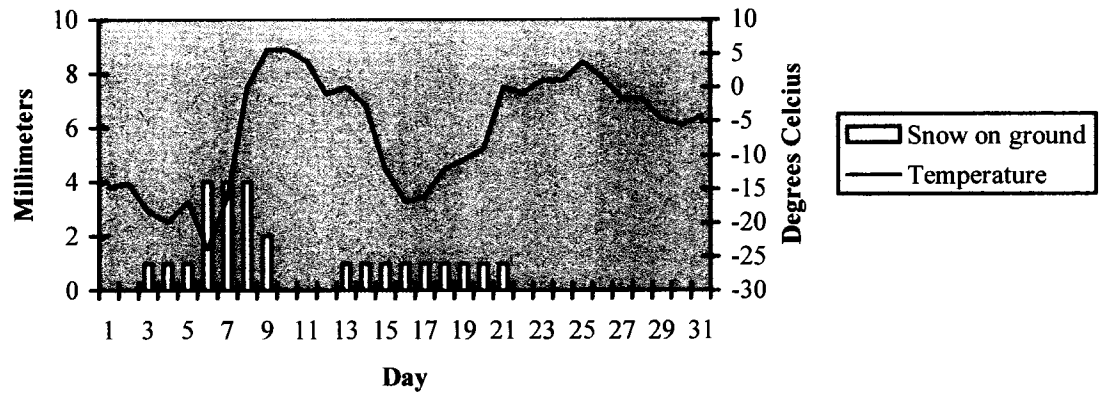

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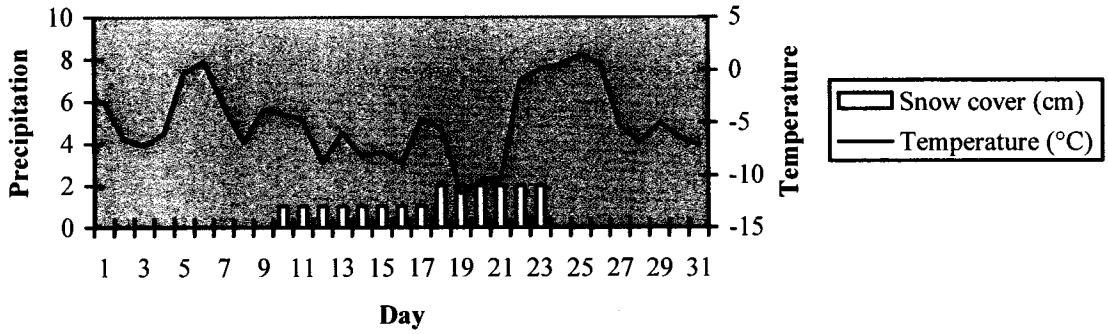

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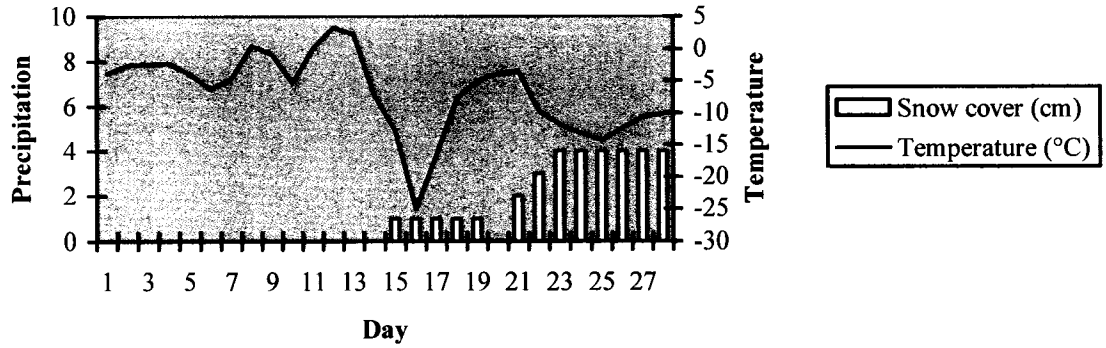

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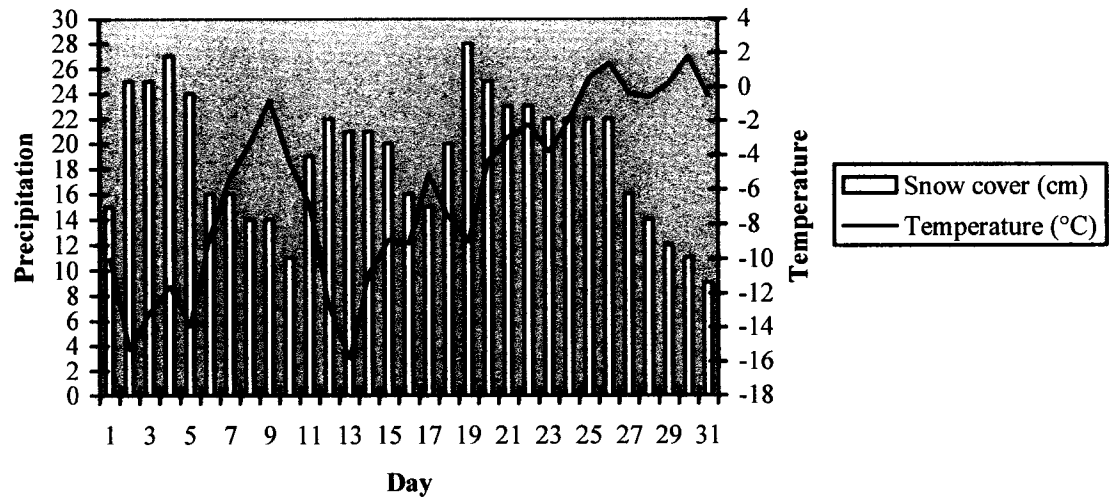
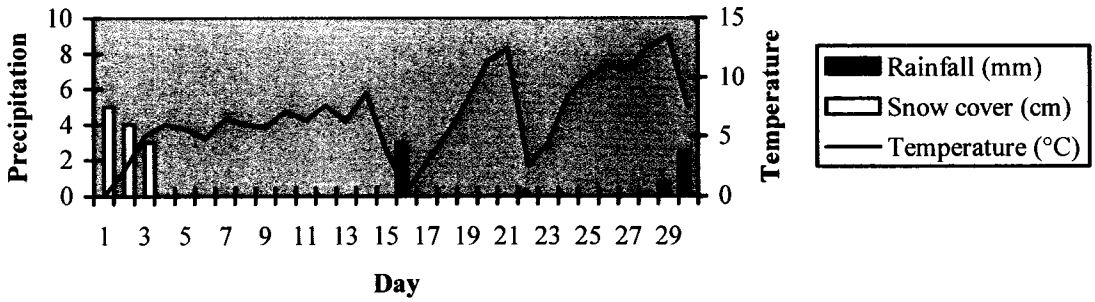
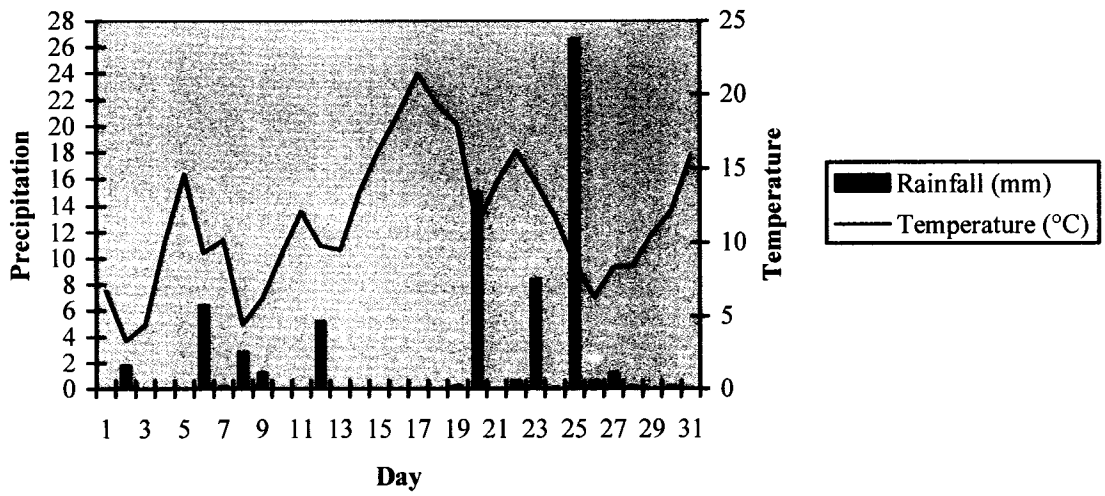


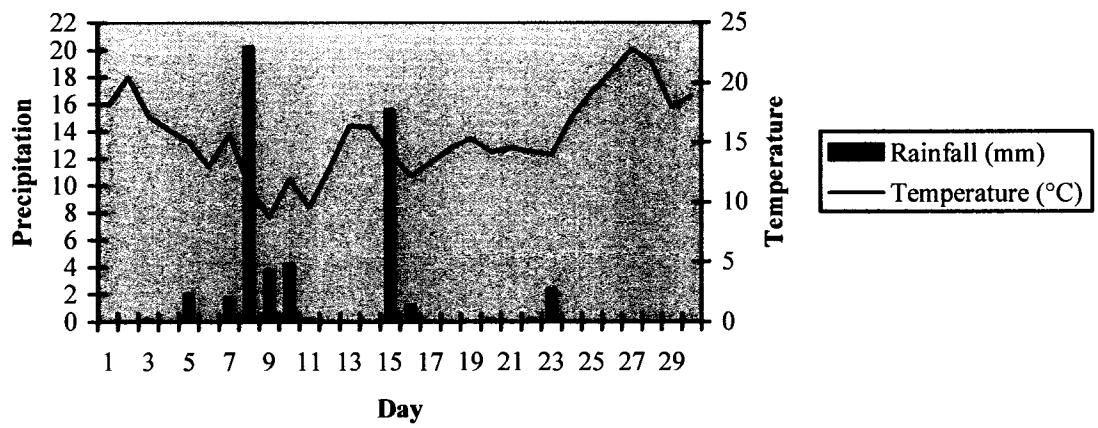
Average Daily Temperature and Precipitation for April 2006



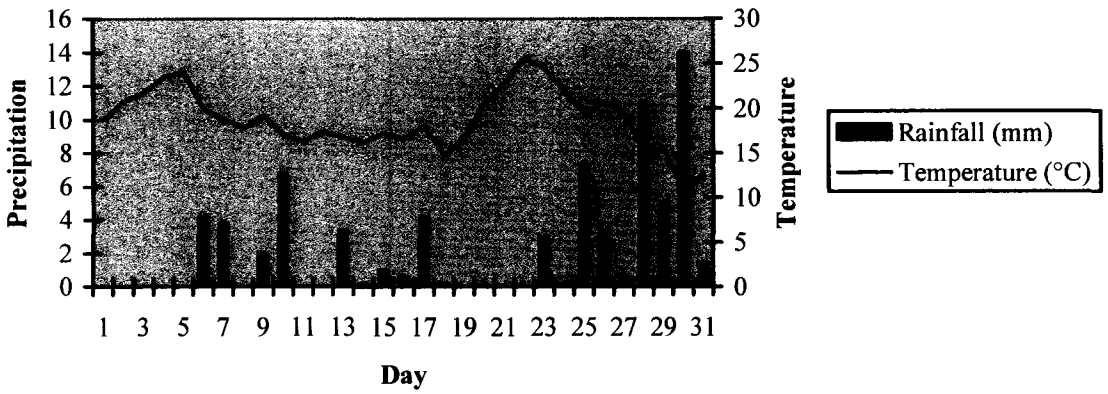
Average Daily Temperature and Precipitation for May 2006



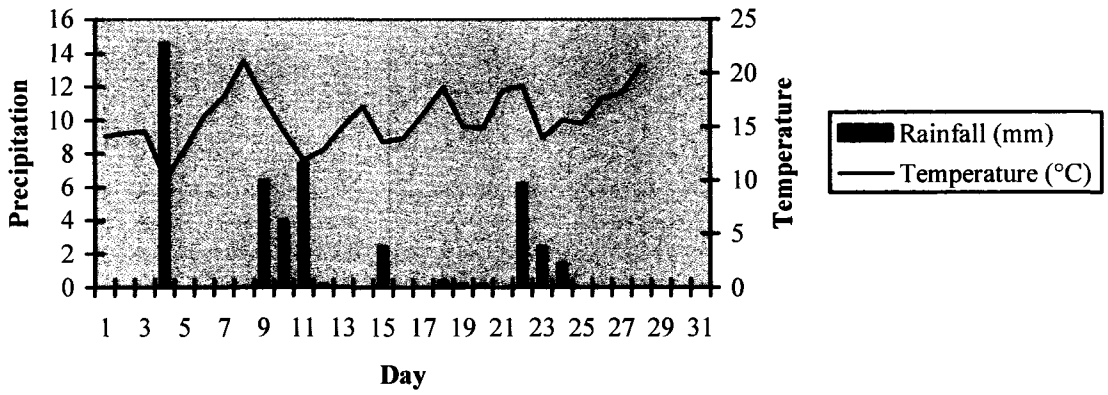
Average Daily Temperature and Precipitation for June 2006



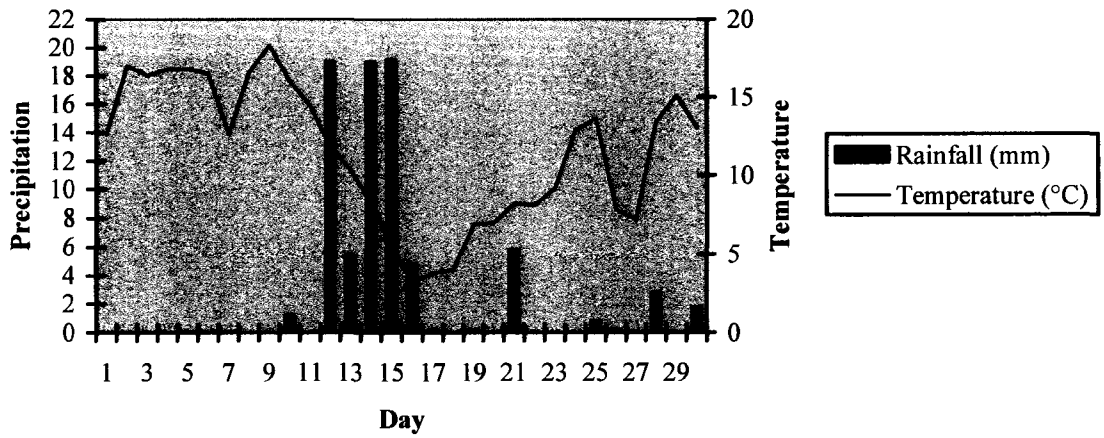
Average Daily Temperature and Precipitation for July 2006



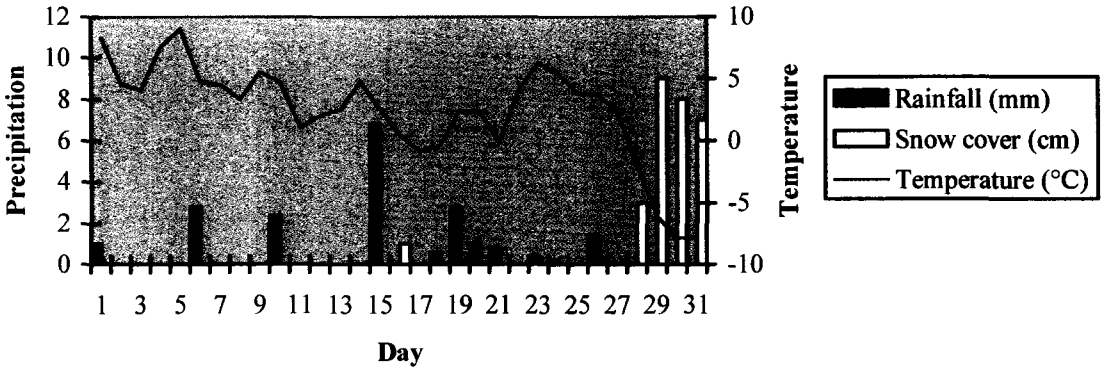
Average Daily Temperature and Precipitation for August 2006



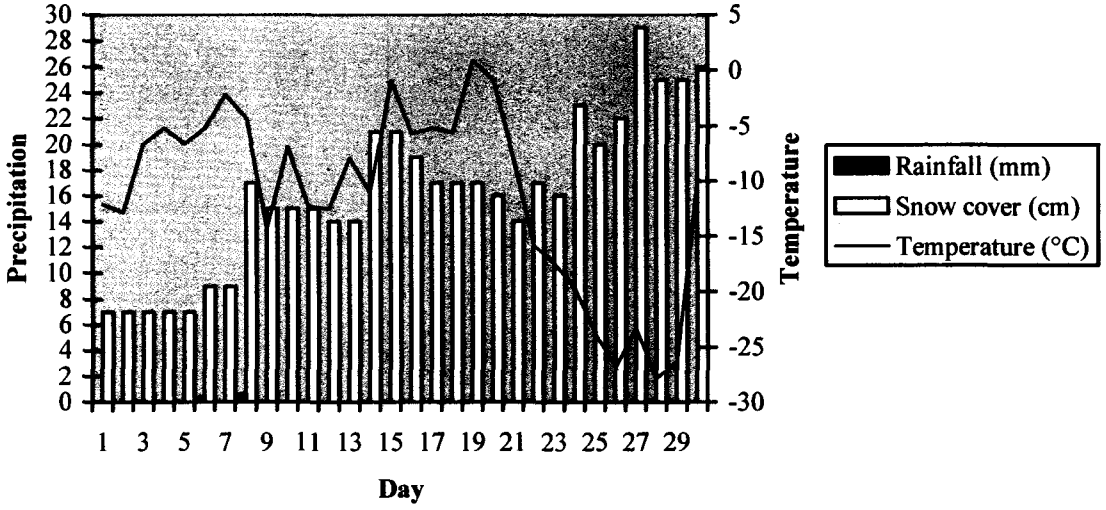
Average Daily Temperature and Precipitation for September 2006



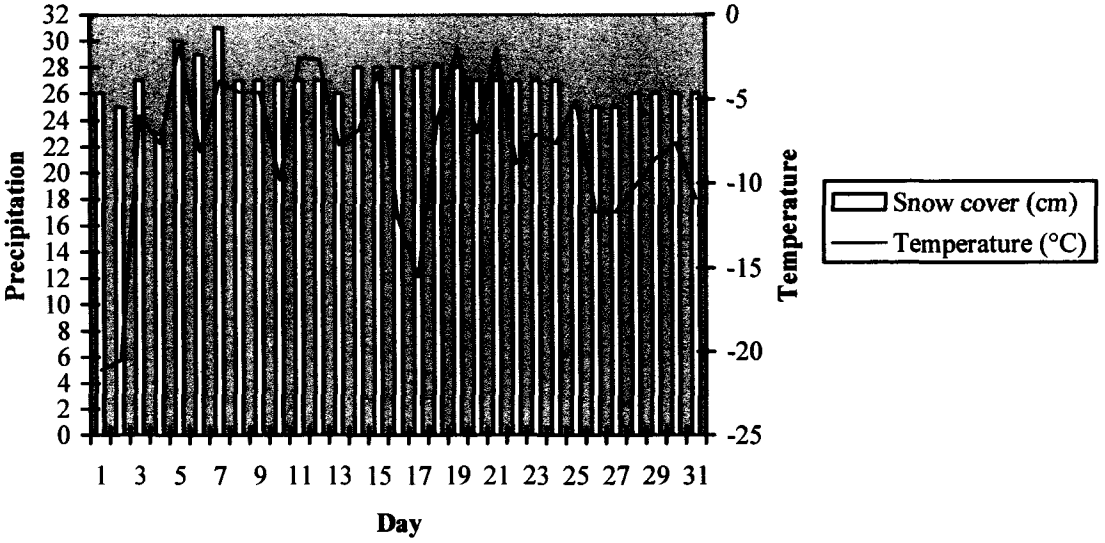
Average Daily Temperature and Precipitation for October 2006



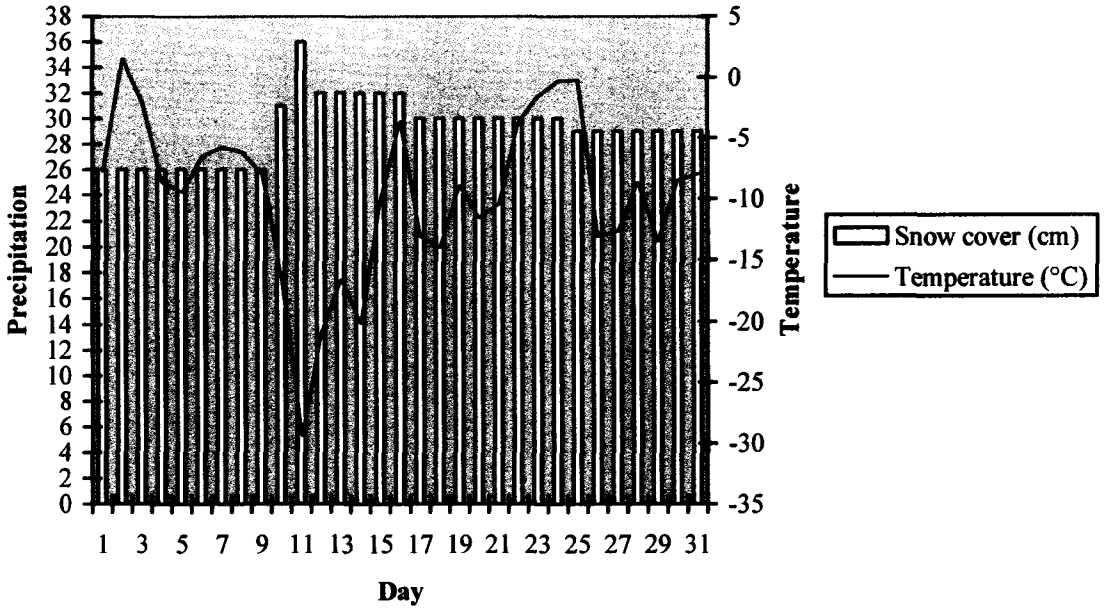
Average Daily Temperature and Precipitation for November 2006



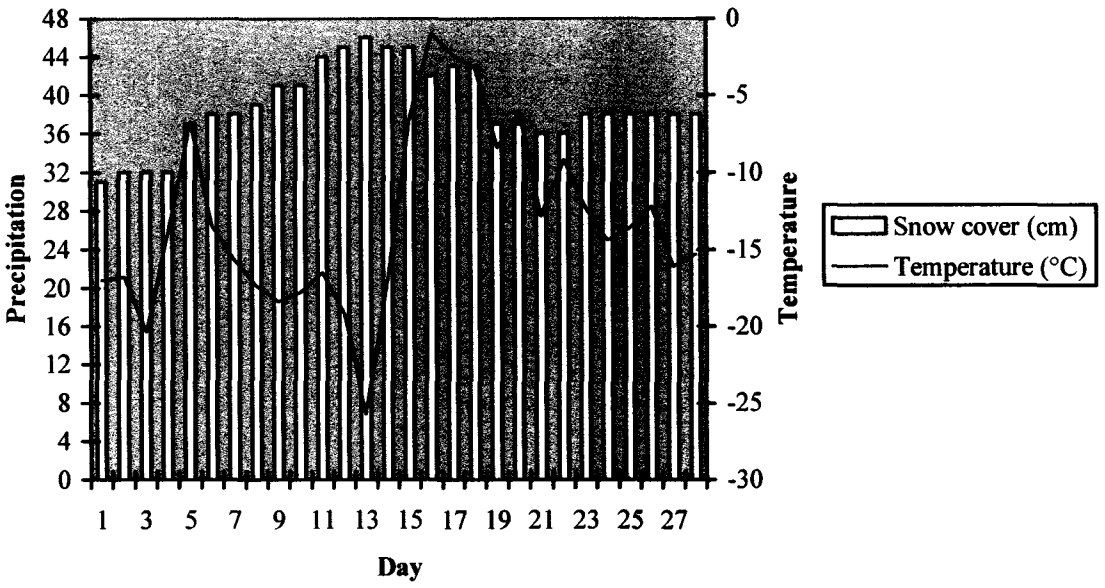
Average Daily Temperature and Precipitation for December 2006



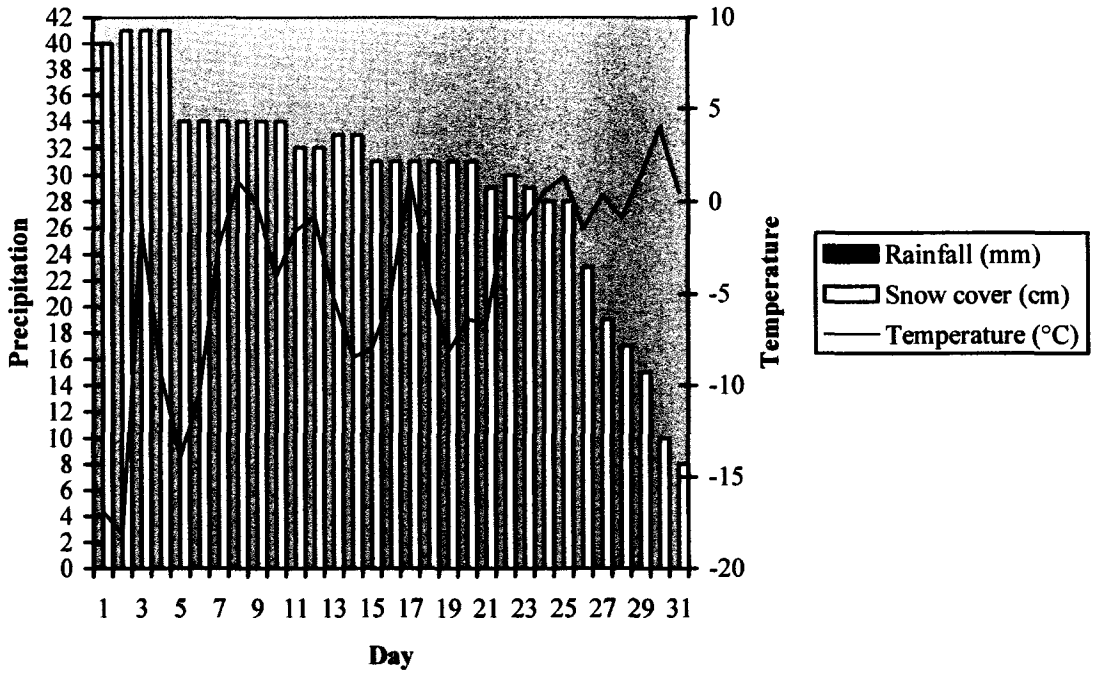
Average Daily Temperature and Precipitation for January 2007



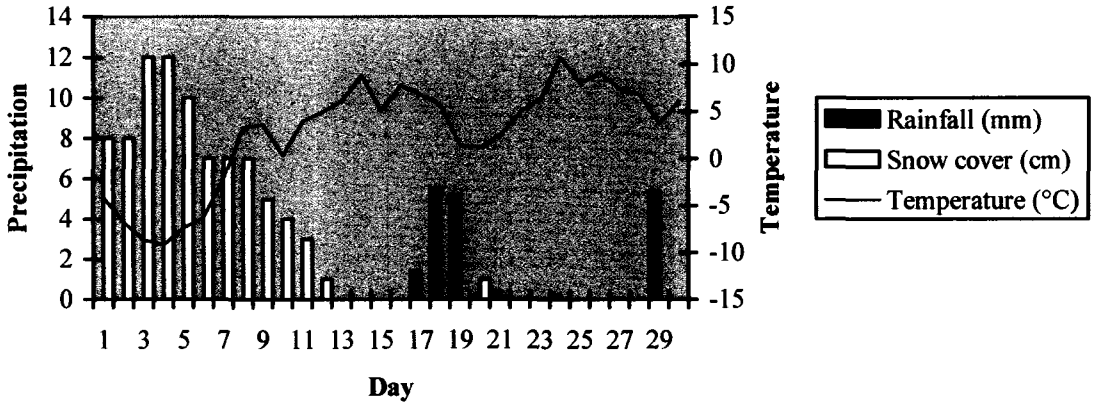
Average Daily Temperature and Precipitation for February 2007



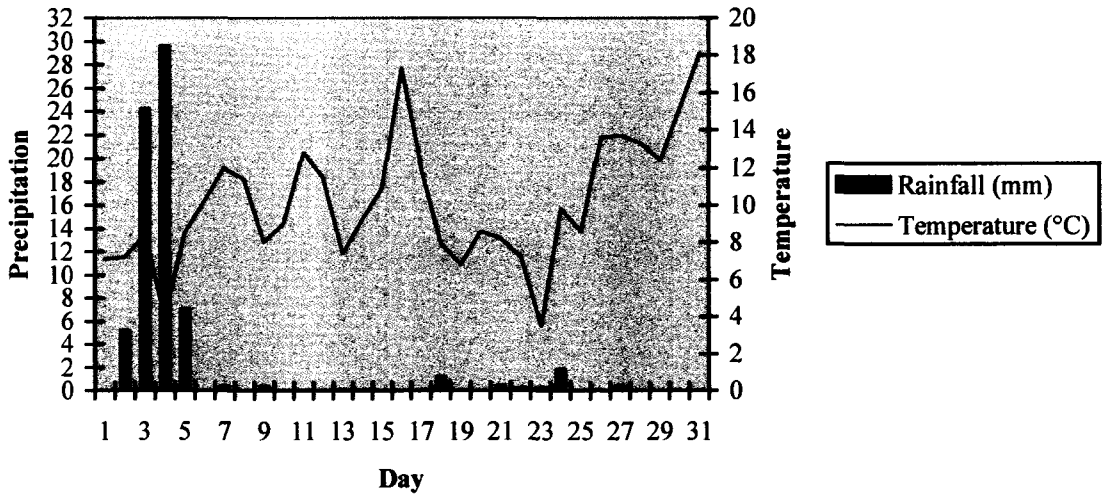
Average Daily Temperature and Precipitation for March 2007



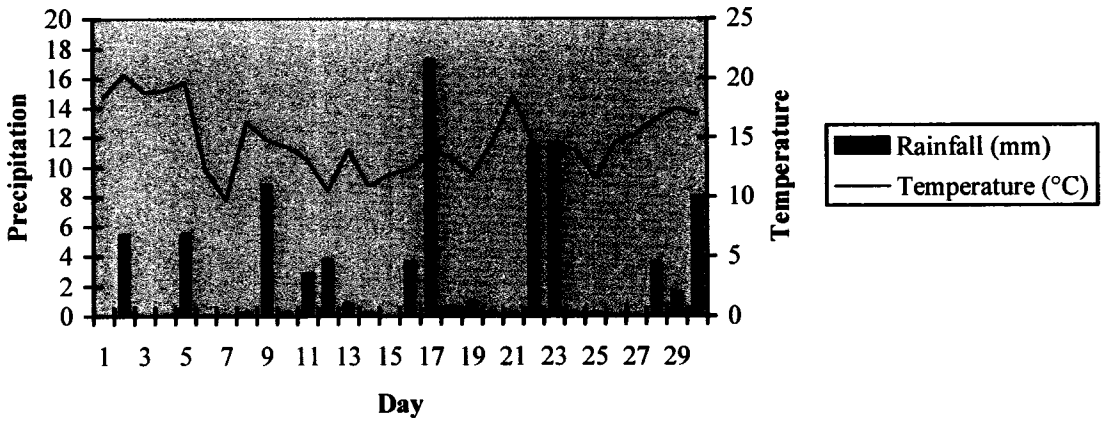
Average Daily Temperature and Precipitation for April 2007



Average Daily Temperature and Precipitation for May 2007



Average Daily Temperature and Precipitation for June 2007



Appendix D. Plates Representing Weathering Stages for Different Skeletal Elements

Plate 1. Long Bones – Stage 0, up to 13 months

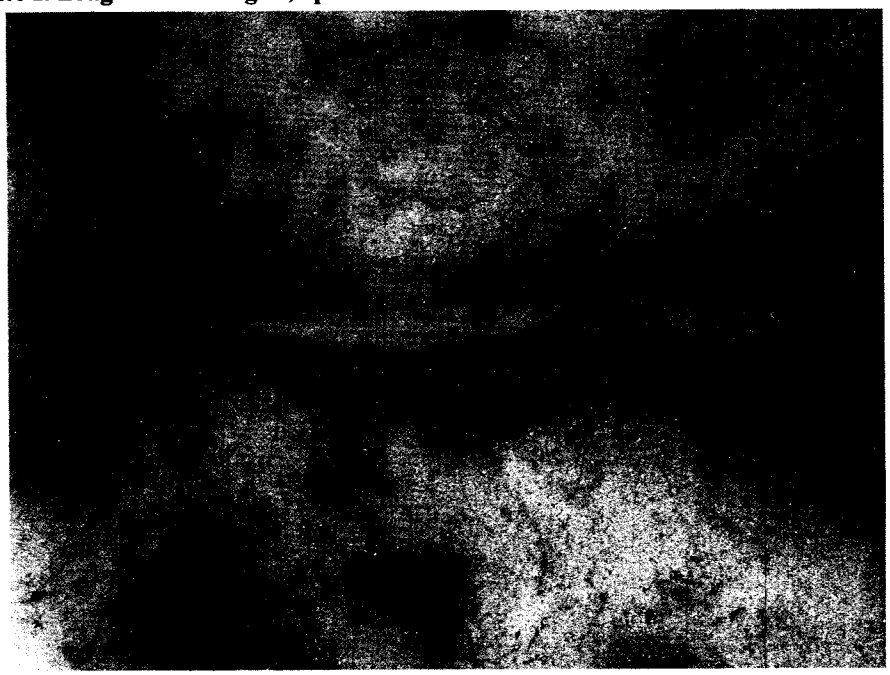


Plate 2. Long Bones – Stage 1, 6 – 22 months

Plate 3. Long Bones – Stage 2, 10 – 32 months

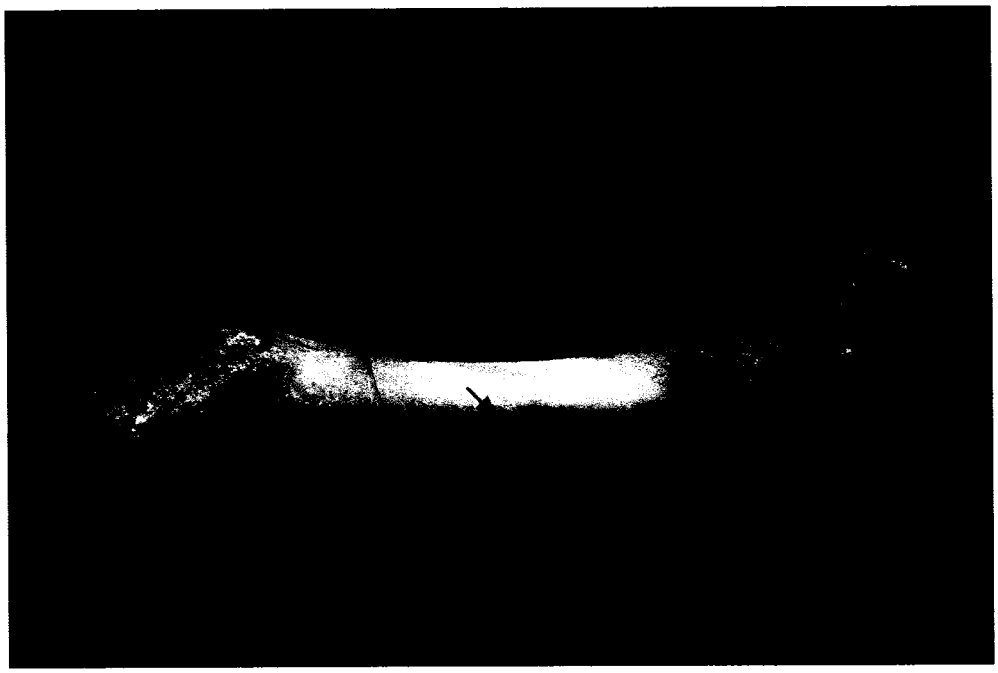


Plate 3.b. Underside of above

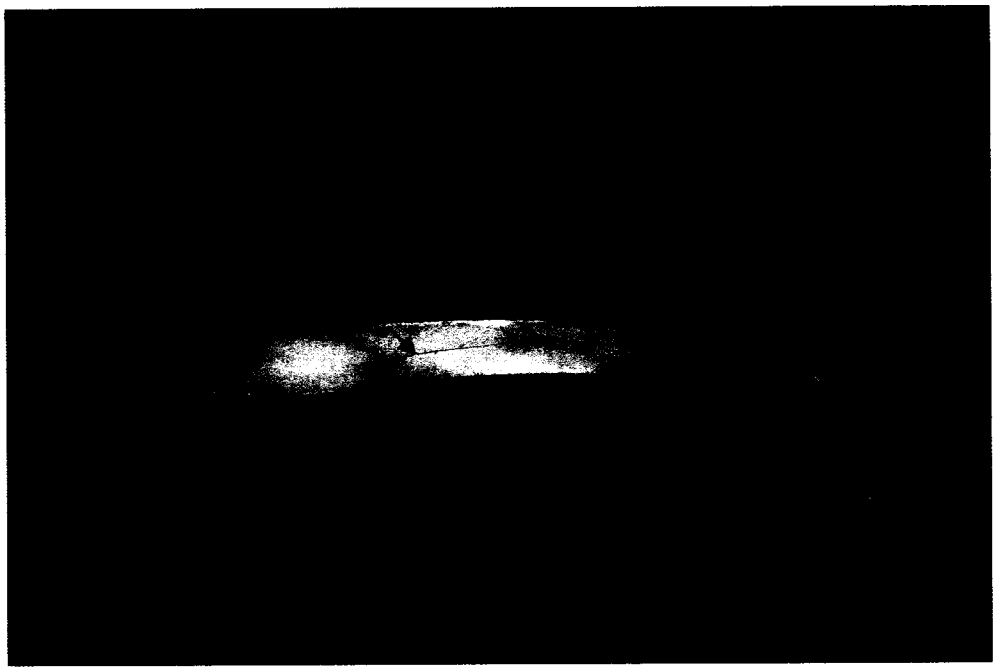


Plate 4. Ribs – Stage 0, 0 – 10 months

Plate 5. Ribs – Stage 1, 6 – 32 months

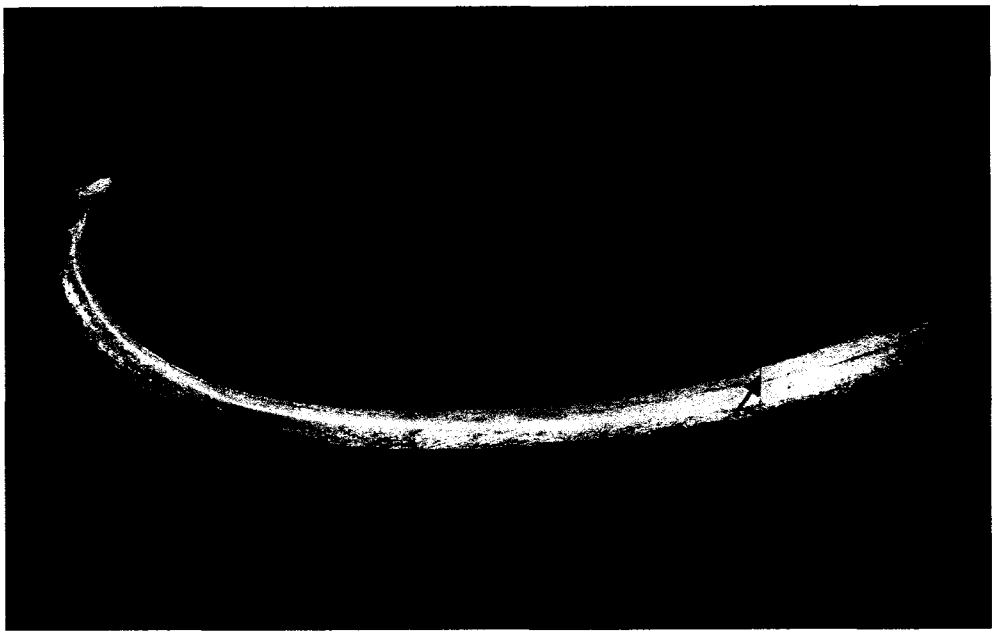


Plate 6. Flat Bones – Stage 0, 0 – 24 months

Plate 7. Flat Bones – Stage 1, 3 – 32 months

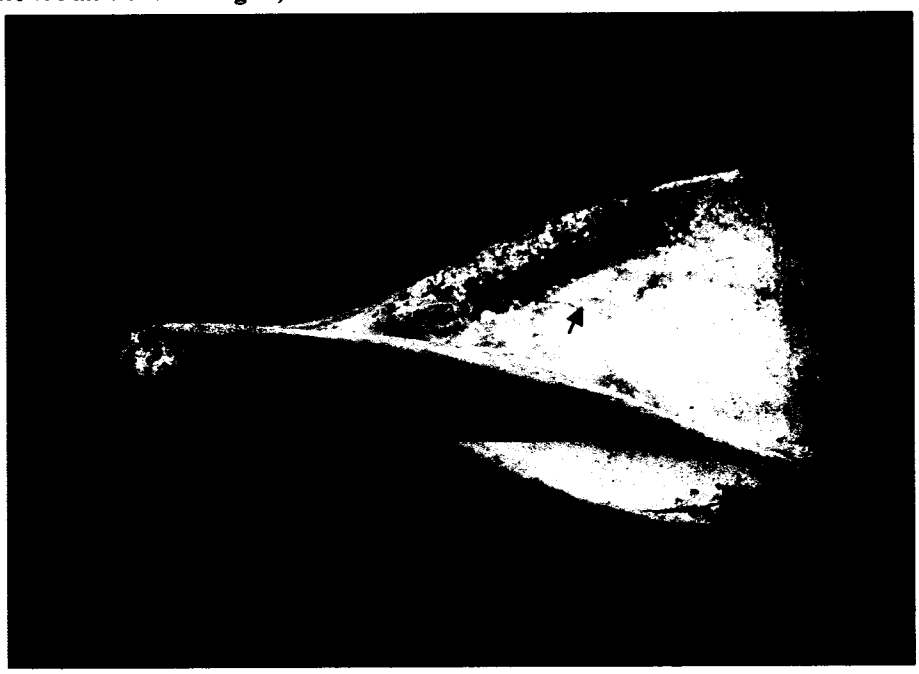


Plate 8. Vertebrae – Stage 0, 0 – 18 months

Plate 9. Vertebrae – Stage 1, 3 – 32 months

Plate 10. Calcanei – Stage 0, 0 – 10 months

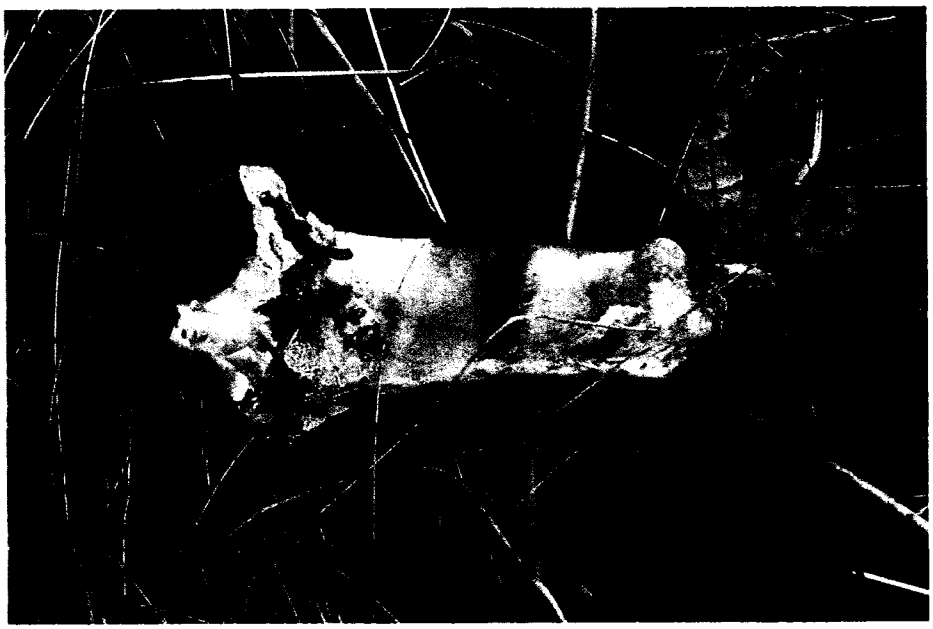


Plate 11. Calcanei – Stage 1, 6 – 32 months

Plate 12. Pig skull – Stage 0, 0 – 9 months

Plate 11. Pig skull – Stage 1, 6 – 33 months