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Paleodemography of the Larson Site (39WW2) Cemetery: How Age-at-Death Methods Influence Model Estimation

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I am submitting herewith a dissertation written by Rebecca Taylor entitled "Paleodemography of the Larson Site (39WW2) Cemetery: How Age-at-Death Methods Influence Model Estimation." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Anthropology.

Lyle W. Konigsberg, Major Professor

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(Original signatures are on file with official student records.)
PALEODEMOGRAPHY OF THE LARSON SITE (39WW2) CEMETERY: HOW AGE-AT-DEATH METHODS INFLUENCE MODEL ESTIMATION

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Rebecca Taylor
May 2013
ACKNOWLEDGEMENTS

When I started at the University of Tennessee in the fall of 2001, I would have told you that I was pursuing a career in forensic anthropology and will be getting myself out of Knoxville as soon as I could. Well several years later and an appreciation for the holistic approach to anthropology instilled by the faculty, I owe my development as a person and as an anthropologist to many individuals.

First and foremost, I would like to thank Dr. Lee Meadows Jantz for taking me under her wing from the very first semester I was a teaching assistant for her osteology class to becoming her assistant at the Forensic Anthropology Center. She has supported me through this entire journey and gave this naïve girl wanting to do anthropology a chance. You have been there through the many trials of tribulations of life, both professionally and privately, and I could not have asked for a better mentor. I know I have gained a lifelong friend and colleague and hope I one day can repay you for all that you have taught me and all of the opportunities you have given me.

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None of this would be possible without the love of my family. I remember when I told my mother that I wanted to pursue anthropology instead of medicine. Her response was “well as long as you can support yourself.” Both my parents sacrificed and made sure that my siblings and I had the opportunities they did not, while allowing us to take our own path. I appreciate being allowed to find my own way. It may have taken me longer than most, but all that matters is that I did the best I could at the time.

I also know I would not have been able to do any of this without my loving husband Anthony. You have taught me so much, including the type of person I should and want to be. Your endless patience with me putting everything but you first is more than anyone could ask. You will always be the epitome of southern hospitality in my eyes. It will take me a lifetime to repay you, but I am looking forward to it.

A special thank you must be given to the Department of Anthropology secretaries, Pam, Pam, Charlene, and Donna. I have worked with you for many years and know first-hand you are the unsung heroes of the department. Thank you for all of the help, especially after I left the department.

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ABSTRACT

The Arikara are one of the last Native American tribes to have direct contact with Europeans. Prior to westward expansion of Euro-American settlers, the Arikara served as middlemen in a complex trade network that brought European goods to the Upper Plains in exchange for fur and food items. In the 18th century with a growing European presence in the region, the Arikara experienced drastic bio-cultural and socio-political destabilization leading to population decline. However, these transitions are unclear because of limited written records prior to the early 19th century. Several hypotheses have been proposed to account for the near extinction of the Arikara tribe including warfare, inter- and intra-tribal conflict, disease, and resource stress.

This research sought to better understand the population dynamics within the Larson Site. The Larson Site (39WW2) cemetery, a relatively unbiased and well-preserved skeletal assemblage (N=643), was re-analyzed to evaluate the demographic variability associated with increased European presence. The main focus of this research demonstrates how age-at-death estimation methods impact the mortality profiles and demographic measures derived from them. Traditional phase-base approaches, long bone skeletal development, Transition Analysis, and multifactorial approaches for both juvenile and adult individuals were used to compute age-at-death estimates for each individual within the cemetery. The point age-at-death estimates served as the basis for survival analysis via parametric hazards models. The Siler model was used to understand the overall pattern of mortality, while the Gompertz and Gompertz-Makeham models were used to explore adult-specific mortality patterns. The results indicate that the high number of juveniles and the relatively low survivorship of adults imply that the...
population may have been experiencing a mortality event, like an epidemic. The high fertility and death rate must be incorporated into future models. Also, the overall patterning of the adult mortality is obscuring any sex-specific adult mortality pattern.

This research is the beginning of a larger project to explore the utility of multi-state models of morbidity and mortality to better explain the population dynamics within the Larson Site and between the Larson and other Arikara villages.
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CHAPTER 1
Introduction

Information that can inform us on the morbidity and mortality experience of past peoples allows us to understand how humans have evolved in response to their environment. Paleodemography provides an avenue for understanding both morbidity and mortality in response to changes in the environment, the socioeconomic conditions, subsistence strategies, and organizational structure of prehistoric populations. This research focuses on the demographic transition associated with European contact in the Upper Plains.

Since bioarchaeology has become its own field of study, data are now available on diet, migration, biomechanics, biological distance, and micro-evolutionary change through the use of analytical techniques such as stable isotopes, geophysical spatial analyses, cross-sectional geometry, geometric morphometrics, and aDNA studies (Larsen, 1997; Buikstra and Beck, 2006; Katzenberg and Saunders, 2008). The basis for most of these data is having a firm understanding of the demographic profile for the population sample being studied. This research hopes to renew the interest in the biology of the Arikara in relation to the increasing presence of Europeans and European trade items, changes to the pre-existing trade networks, the migration of other tribes into the Missouri River Valley, and several other independent factors affecting the health, demography, nutrition, and sociocultural structure of the Plains people in the protohistoric time period. The diversity of the people and the outside pressures experienced by the Arikara provide an excellent basis for comparative research on the health and mortality changes caused by contact with Euro-Americans. The incorporation of statistical models that can integrate both health indicators and demographic parameters has the potential to create new,
independent tests of the archaeological and historically derived hypotheses. However, prior to understanding the changes in health of the population, a thorough understanding of its demography is necessary.

Exploratory archaeology of the late 19th and early 20th century led to federally mandated salvage projects that preceded the damming of portions of the Missouri River in South Dakota. As a by-product of these projects, large collections of skeletal and cultural materials from Plains Indians were amassed. Since the advent of the Native American Grave and Repatriation Act in 1992 and several subsequent federal and state laws (Ousley et al., 2005; Buiskra, 2006), the availability of large skeletal samples, like that from the Larson Village (39WW2), are dwindling. Larson Cemetery (39WW2) in Walworth County, South Dakota, represents one of the largest single pre-industrial sites in the Northern Plains and has been heavily studied since its excavation making it ideal to investigate the utility of newer paleodemographic methodologies compared to what has been previously published. The advent of new methodologies and the diminishing access to Native American skeletal materials necessitates a re-evaluation of materials still available and the implementation of statistical methods, which may be able to express differences in mortality and morbidity over that which was previously available. Questions of the effect of skeletal age-at-death estimation methods on the mortality profile, the utility of hazard models versus life tables for model building, and the differences in male and female mortality patterns will be addressed in this research.
Issues of Interpreting Population Change

Native Americans of the Great Plains experienced a micro-evolutionary shift socio-culturally and biologically with European contact, which translates into demographic changes. Bocquet-Appel (2008: 657) defines a demographic transition as “a quantitative leap in the self-regulated flow of population inputs and outputs that is determined by qualitative change in the causal mechanisms underlying the regulation.” Researchers have focused on the use of paleopathology and paleodemography to demonstrate the affect contact had on Native Americans in the New World, but often in isolation of one another.

The skeleton has the potential to clarify the biological and cultural impact of disease in Native Americans if sounds methods and statistics are utilized. However, a number of limitations in assessing health and well-being from the skeleton through the use of skeletal lesion frequency, life expectancies, and average age-at-death exist (Wood et al., 1992a).

For example, a physical manifestation of stress indicates a person lived long enough to develop the biological marker (elicit an osteological response to a physiological stress), but it is unclear whether the individual who had the marker is “healthy” compared to an individual without such a marker (Wood et al., 1992a). Acute diseases, like most infectious diseases, are rarely expressed in bone, which means that most epidemics will leave, at best, non-specific evidence in a skeletal assemblage. Conversely, most skeletal evidence visible in the skeleton reflects chronic conditions. Smallpox, a viral disease suspected to have caused the drastic depopulation of Native Americans across the United States, is an acute illness that leaves little to no skeletal evidence. Many factors affect the pathogenesis in a person with a pathological condition including: 1) the age of onset, 2) the individual’s nutritional status, 3) the immune
response of the person, 4) the infectious agent, and 5) social conditions of the population (Ortner, 2003).

Also, a shift in the average age at death could be interpreted as an increase or decrease in the risks of death experienced by individuals within the population. Johansson and Horowitz (1986) state that treating mean age-at-death as if it were equivalent to life expectancy is only legitimate when the population is stationary during the period under consideration. Hence, it must be demonstrated that the population is not growing or declining and was closed to migration. For example, a fast growing population could have a mean age at death that seems low, which would make one suspect an unhealthy population. This could be offset if population growth and decline rates were incorporated into the model. Since the mean age-at-death collapses all age data into one number it obfuscates the overall distribution, under-enumeration issues, and age heaping from poor age estimation. Also, it is often presumed that age at death is directly related to overall health of the population, but this overlooks individual frailty (Vaupel 1979) and the socio-cultural mitigation of individual-level frailty.

The issue with previous research on the health of the Native Americans in the Upper Plains over time and space is the lack of integration of paleodemography and paleopathology. These two fields of research, if combined analytically, permit improved interpretation of the morbidity and mortality of past populations.

Williams (1994) provides a very good review on the demography and paleopathology of Archaic and Woodland skeletons from the Northern Plains. Similar overviews are available for the protohistoric and historic Indians of the Northern Plains, but do not incorporate the theoretical and methodological advances in paleodemography or paleopathology (Owsley, 1992;
Johannson and Owsley, 2002). Owsley et al. (1977) and Owsley and Bass (1979) provide a similar description of the Larson Site (39WW2) village and cemetery. Palkovich (1981) has provided an overview of the Arikara from the Mobridge site (39WW1) as did Bass et al. (1971) for the historic Leavenworth site (39CO9). Otherwise, most of the literature has focused on description and prevalence rates of specific diseases discovered during analysis of the skeletal material from these sites (Owsley and Bradtmiller, 1983; Kelley et al., 1994; Mann et al., 1994). The Larson Site is an ideal site to study not only the population structure, but how it changed in response to different stresses associated with the increasing European presence in the region as well as test the utility of new methods in paleodemography.

Owsley (1992) is an early attempt to synthesize the plethora of data available from the Northern Plains to understand the demographic impact of infectious disease as a result of contact. This paper focuses on the trends within the Northern plains noting that there is significant temporal variation in the mortality profiles of the individual sites through a comparison of the distribution of deaths for each age cohort in the life table, and suggests that the post-1700 Arikara were in a period of decline. The Larson site has increasing childhood, adolescent, and young adult mortality rates with few older adults, which is supported by the settlement patterns (Owsley, 1992). More recently, Johansson and Owsley (2002) examine the welfare history of the Great Plains from a contextual perspective. They note that in order to explain the skeletal data one must 1) understand how the general environmental influenced mortality, 2) consideration of specific historical circumstances relating to contact-sensitive mortality, and 3) consider how the entire age-at-death distribution produced the mean age-at-death. However, this work did not include the Larson site, because the mean age-at-death from
the extremely low, 13.2, because of the large number of infants rather than contact shock. The other Arikara skeletons, dating from 1690 to 1740 suggest that it was very unlikely that the life expectancy at birth was as low as their mean age-at-death. The Archaeological evidence suggests that the Arikara were able to capitalize on their role as middle men in the trade network, had good nutritional resources for most of the year, but lived in crowded lodges within fortified villages. The combination of the environmental and socio-cultural factors affected the overall health of the Arikara Indians of the Northern Plains.

The question that should be raised is if major transitions like the transition to agriculture and industrialization are apparent demographically, can we observe smaller, more localized transitions? Several demographic and epidemiological transitions have been noted in the literature and provide the basis for examining the demographic patterns in the Larson Site (39WW2), Walworth County, South Dakota. Recent work on the Black Death has demonstrated the possibility of understanding demographic processes associated with smaller scale events (Margerison and Knusel, 2002; DeWitte and Wood, 2008; DeWitte, 2009; Redfern and DeWitte, 2011), even though it has long been believed that once an epidemic is over the former levels of mortality will be regained within a short period of time (Weiss, 1973). If the Arikara were in a period of decline after 1700 and the Larson Village represents a population that experienced a smallpox epidemic could this trend be visible through the application of recent paleodemographic methods. It is imperative to incorporate skeletal indicators of stress into demographic models to better understand the processes associated with rising Euro-American presence in the Missouri River Basin.
Age-at-death Estimation’s Impact on Demographic Model Building

Ubelaker states that “accurate evaluations...have become increasingly essential to the interpretation of population-environmental relations” (1989: 1). However, paleodemography is still relatively under-utilized to interpret population structure from a skeletal sample. Bocquet-Appel and Masset (1982) showed that paleodemographic age estimates using traditional methods are inherently biased towards the age composition of the modern known age-at-death reference samples. The skeletal age indicator corresponds to a mean age in a reference sample where the mean age depends on the age structure of the reference sample. In most traditional cases, an osteological trait (Y) is regressed on age (X). Bocquet-Appel and Masset (1982) demonstrated that the linear regression of an osteological trait on age from two reference samples with very different mean ages at death were very similar. In paleodemography, the goal is to determine the probability that a skeleton is a certain age (X) given the appearance of an osteological trait (Y). When X is regressed on Y, the result is age mimicry of the reference sample.

As a result of the “Farewell to Paleodemography” outlook by Bocquet and Masset (1982), several researchers have sought to improve age-at-death estimations, which has led to the development of statistical methods to solve the problem of age mimicry and provide more accurate and informative age-at-death estimates (Konigsberg and Frankenberg, 1992, 1994; Boldsen et al., 2002; Holman et al. 2002; Hoppa and Vaupel, 2002; Muller et al., 2002). These recent advancements in age-at-death estimations, called the Rostock protocol (the protocol is named as such, because it was developed at a series of meetings held at the Max Planck Institute for Demographic Research in Rostock, Germany), use maximum likelihood estimation and Bayes’ Theorem to produce unbiased estimates, including the point estimate and error distribution of that estimate. The idea for the Rostock Protocol is to estimate the cemetery
sample age-at-death distribution and then estimate individual age-at-death using Bayesian inversion (Konigsberg and Frankenberg, 1992, 1994). The Rostock protocol requires 1) estimation of the probabilities of certain age indicators given age from a reference sample, 2) observation of the frequency of skeletal indicator of age in target sample, 3) calculation of the maximum likelihood estimates for the parameters of a parametric age-at-death distribution, and 4) using Bayes’ Theorem to determine the individual ages (Hoppa and Vaupel, 2002). Using the Rostock Protocol, Muller and colleagues (2002), estimated individual ages-at-death for a simulated target sample and compared the results to those obtained using traditional methods. They found that the protocol estimates were close to the true ages in the simulated target sample and were not biased (Muller et al. 2002).

This leads to the question as to whether age-at-death estimation methods, which follow the Rostock Protocol, provide a more informative age-at-death estimates for the Larson Site cemetery. **H1: The implementation of Transition Analysis, a modified version of the Rostock protocol developed by (Boldsen et al., 1998, 2002), and multifactorial approaches for juveniles (Shackelford et al., 2012) and adults (Uhl, 2013) will not produce different age-specific mortality curves from the published literature, which is based on life table methodologies.**

Traditional adult age-at-death estimation methods, utilized in the initial demographic analysis of the Larson Site, provided constricted age ranges with most of the older adults having open-ended terminal phases with ages of 50+ and were based on a single age-indicator, the pubic symphysis. Also, the age-at-death methods were constricted to fit the life table age distribution in which individuals were grouped in age categories ending in a 5 or 10. Further, the very old
were not accounted for because of methodological limitations of the aging method, as the reference population for which the methods were based on had few old individuals. Owsley (personal communication) acknowledges the biases inherent in the early publications and states that he has re-assessed the adult age-at-death estimates for the Larson Site, but has not published these new estimates. The lack of age-at-death estimates utilizing recent advances in age-at-death methodology combined with the fact that the Larson Site skeletal materials are heavily used for anthropological research necessitates the re-evaluation of the skeletal material. The application of Transition Analysis has the ability overcome the early limitations of age estimation within a Rostock Protocol framework. Buikstra et al. (2006) provide evidence for the utility of Transition Analysis in capturing the very old within a population and Milner and Boldsen (2012 a, b) note that the prediction interval for older individuals is narrower than middle-aged individuals when using a prior distribution. Alternatively, a multifactorial method (Uhl et al., 2011; Uhl, 2013) that is based on transition analysis and has shown promise in the forensic context may provide improvements over the single indicator method, Todd (1920), used in the original demographic analysis of the Larson Site. This method provides an avenue for exploring how to combine scores for skeletal indicators of age from previously examined sites or sites that have been repatriated using Bayesian inference. As such, it can provide new information useful for model construction over that which was available previously.

The bias and inaccuracy issues inherent in the adult age-at-death estimates are also relevant to the juvenile age-at-death estimates in the original demographic analysis of the Larson Site. Age-at-death estimates for juveniles tend to be an average or weight of several traits rather than being derived from the statistical computation of scores from specific morphological features.
within the skeleton. Owsley (1975) used Moorrees et al (1963 a, b) as the basis for ages, which is considered one of the best methods for assessing dental age in juveniles. However, several of the juvenile individuals do not have associated teeth or do not have the teeth used as standards within these works. Furthermore, Owsley (1975) states that the scores for the premolars were used as the basis for many of the age estimates over that of the other available tooth scores, so did not account for the full variation within the entire dentition of the individual. A multifactorial, maximum likelihood estimation method that is able to combine the scores from multiple teeth (Shackelford et al., 2012) may produce significantly different estimates over that which was originally determined by Owsley and Bass (1979). Also, dentition-based methods were not available for very young infant or fetal remains during the initial analysis of the Larson Site materials in the 1970s.

The second aspect of this research question focuses on the application of parametric hazard models to determine if the new age-at-death methods derived through transition analysis and multifactorial analysis will produce different mortality patterns compared to those published for the Larson Site (39WW2) in Owsley and Bass (1979). Owsley applied model life table methods for the original demographic analysis of the Larson Cemetery. These methods are outlined by Acsadi and Nemeskeri (1970) and are one of the predominant tools used in early paleodemographic research. The life table approach has two assumptions: 1) the population must be stationary in which there is equal birth and death rates with fixed age-specific mortality rates and 2) the population is closed so there is no in or out migration of individuals. Owsley justified the use of this method because of the short time segment of the cemetery, as indicated by the archaeological record, so any vital statistical changes would not be reflected in a cemetery.
that only represented a few generations, but this is an argument for stability rather than stationarity.

Gage (1989, 2000) suggests that new age techniques may result in life tables that resemble those of historic populations. The mortality curves for prehistoric populations often are truncated suggesting lower life expectancies, which was the result of traditional age-at-death estimation methods. A method that is able to capture older individuals may improve the parameter estimates. However, many of the published distributions indicate a high number of deaths in early adulthood with few individuals surviving (Aykroyd et al., 1999; Howell, 1982; Milner et al., 2000; Paine, 1989; Wilson, 2010). Owsley and Bass (1979) presented data on the mortality, survivorship, age-specific probability, life expectancy, and crude mortality rate. These data can be directly compared to hazards’ derived data to determine congruency in estimates and support the application of hazard models in paleodemography. Hazards allow for data smoothing in order to obtain the age pattern of mortality, so improve the reliability of life tables from anthropological data. Furthermore, hazard models establish the foundation to address “health” from a paleoepidemiological perspective by permitting the incorporating indicators of “health” to demonstrate how these indicators affect the mortality of the population.

Hazard analyses provide a means to address several of the issues outlined in the “osteological paradox,” including demographic non-stationarity, selective mortality, and hidden heterogeneity (Wood et al. 1992a, see Chapter 3 for further discussion) as these are relevant to studies examining the biological costs of cultural behavior and disease-causing conditions (Wright and Yoder, 2003). Additionally, the representativeness of the skeletal sample to a once living population is fundamental to the construction of mortality profiles. Gage (1988, 2000) indicates
that there are major limitations to the expectation-of-life calculations because of the underenumeration of infants. Gage (2005) provides further information to support this opinion. It is the combination of lack of infants and children in the skeletal sample and the under-aging of adults that creates life tables atypical of historic populations. The Larson Cemetery skeletal population is unlike most sites available for research because the population is largely composed of juveniles in a good state of preservation. Even though Gage (2005) suggests that underenumeration and truncation of the old may actually cancel each other, so the life tables once presumed to be flawed may not be as erroneous as first thought, it is important to evaluate if this is in fact the case.

**Sex-Specific Adult Mortality**

Typically, it is assumed that all skeletons within a population have the same risks for morbidity and mortality, but this is not the case because individuals differ in their risks of disease, fertility and mortality (Weiss, 1990; Wood *et al.*, 1992a). Owsley and colleagues (Owsley and Bass, 1979; Owsley and Bradtmiller, 1983) have suggested a higher number of young adult females within the protohistoric Larson Cemetery and attributed this to the higher risk of death associated with childbearing. Likewise, research has demonstrated a high risk of death for younger females in the Middle Mississippian period (Wilson and Steadman, 2008; Wilson, 2010). Specific segments of the population have a higher risk-of-death, like the very young and very old, but not all variation can be easily measured because of hidden heterogeneity and individual frailty. If hidden heterogeneity is suspected on a sub-section of the population, the mortality profile of a combined dataset would compromise interpretations of the
demographic processes within the living population (Vaupel and Yashin, 1985; Wood et al., 1992b). **H2: A difference between adult male and female mortality does not exist in the Larson Village Cemetery.** The previously observed differences in age-at-death distributions between males and females may be a result of biases inherent in the age estimation method’s reference population. Reference samples can cause significant biases and lead to misleading interpretations if not adequately handled (Milner et al., 2000). The published survivorship for adults indicates that all individuals died around the age of 40 years, which does not reflect the entire lifespan of the once living individuals. As such, it is unclear if the pattern observed by Owsley and colleagues is a reflection of the aging method or is a real pattern in the population.

**Summary**

This research is the first step in a larger research agenda to better understand the health of the Arikara in the Middle Missouri region and focuses on the demography of the Larson Cemetery population. It is nearly impossible to separate health and demography because individuals analyzed from a cemetery are a biased reflection of the once living as outlined in the “osteological paradox” (Wood et al., 1992a); but one cannot ascertain health without creating a complete demographic profile of the population. Recent advances in age-at-death estimations and paleodemographic model building permit more informative demographic reconstructions and can lead to addressing more in depth questions as to the “well being” of a population as it is defined by Wood (1998) and Usher (2000). However, it is not until an accurate age-at-death profile is formed that one can create models that truly illustrate the factors influencing cemetery
sample formation (Boldsen, 2007). Poor choices produce inaccurate age estimates and thus misleading age-at-death distributions. In order to adequately reconstruct past population dynamics, appropriate mathematical models must be applied. Models that integrate demographic and epidemiological data need to be applied to determine the best fit of population parameters to fully understand the age structure of a skeletal population and heterogeneity and frailty within a population. This research focuses on the former, because it is fundamental to, and the first step towards, understanding well-being and selective mortality.
CHAPTER 2
Archaeology and Cultural Affiliation of Larson Site (39WW2)

Background
The Larson Village Site (39WW2), one of the largest Plains Indian cemeteries to be excavated in South Dakota, was among a number of archaeological sites excavated and investigated as a result of the Missouri Basin Project between 1946 and 1969, under the direction of the Smithsonian Institution, National Park Service, and several universities (Lehmer and Jones, 1968; Lehmer, 1971; Bass, 1981). The Missouri Basin project was created after World War II in response to the construction of four large reservoirs that were being built along the Missouri River in North and South Dakota (Lehmer, 1971). Prior to the 1960s, little data existed on the skeletal biology of the individuals that once inhabited the Great Plains with the exception of work by M.W. Stirling and W.H. Over, who were responsible for the documentation of more than 200 archaeological sites in the Northern Plains (Bass, 1981; Sigstad and Sigstad, 1973). The Missouri Basin project resulted in approximately 10% of the known archaeological sites being investigated. The skeletal material excavated represented a heterogeneous mixture of the various populations that inhabited the region over several temporal periods (Bass, 1981).

Several South Dakota Native American villages, including Leavenworth (39CO9), Larson (39WW2), Sully (39SL4), Mobridge (39WW1), and Rygh (39CA4), were excavated and proved the Arikara had a long temporal occupation of the area (Hurt, 1957; Bass et al., 1971; Jantz, 1972; Krause, 1972). These sites are believed to be associated with the Arikara tribe; although several other tribes also inhabited the area, including the Mandan and Hidatsa tribes. The Arikara of the late prehistoric, protohistoric, and historic periods were Caddoan speaking
semi-sedentary horticulturalists who occupied villages along the banks of the Missouri River in South Dakota. The river drainage system and the alluvial bottoms associated with it provided an ideal location for prehistoric populations and served as a means for communication, trade, and resource exploitation.

Excavations at the Sully Site (39SL4) confirmed that the Arikara buried their dead in defined areas, near the village and served to guide later excavations associated with Arikara villages (Bass, 1964). Ethnohistoric data from the Leavenworth Village provides much of the cultural history known about the Arikara. This village was well documented in the early and middle 19\textsuperscript{th} century by several Euro-Americans, including Lewis and Clark in 1804.

**Cultural Affiliation**

Early biological distance studies, which utilize quantitative traits to measure degree of population divergence to infer evolutionary history, suggest a Mandan relationship for the Larson Village Site (39WW2) based on tribal distributions and burial patterns (Bowers, 1967). However, Lin (1973) demonstrated that multivariate analysis can clearly distinguish Arikara from Mandan crania, which was supported by a discriminant function analysis by Jantz (1973). Craniometric analyses of the Larson Village skeletal material indicate a clear similarity to Arikara with only minor differences, which can be explained by secular change, to the exclusion of Mandan (Jantz, 1973; Jantz 1974; Owsley and Jantz, 1978). Furthermore, Owsley and colleagues (Jantz et al., 1978; Owsley and Jantz, 1978; Owsley et al., 1982; Owsley et al., 1981; Byrd and Jantz, 1994) have demonstrated an Arikara affiliation for the Larson Site and demonstrate through craniometric analyses of several Upper Missouri tribes that the individuals
in the Larson Site are associated to the Leavenworth Site, which is historically known to be Arikara. The Leavenworth Site represents the most recent of the Arikara sites temporally, has the most secure dates, and has historic information to associate it with the Arikara tribe (Bass, 1966; Bass et al., 1971). Recent craniometric literature using Cartesian coordinates of cranial landmarks through geometric morphometrics confirms the earlier works of Jantz and colleagues that the Larson Village Site is associated with several other geographically similar Arikara sites, including Leavenworth, using craniometrics (McKeown and Jantz, 2005). However, Byrd and Jantz (1994) have found significant variability in the crania in the Leavenworth Site. This has been interpreted as reflecting variation within the Arikara tribe, because Arikara villages were known to have been separate socio-political complexes, which could have translated into limited genetic flow between villages. However, during the post-contact period, village organization structure was disrupted causing the coalescence of several villages spanning the entire Arikara territory. Thus the variation found in the Leavenworth Site could represent differences within, or multi-components among, the Arikara to the exclusion of the other tribes in the Middle Missouri region.

The Larson Site burial customs are similar to what has been seen in other Arikara cemeteries where the burials are primary interments with wood covering the grave (Snortland, 1994). Ethnographic data indicate the Arikara had formal burial areas in proximity to their village with burials being in a flexed or semi-flexed position and oriented facing the village (Orser, 1980). Scaffolding was no longer a primary custom in the protohistoric, but was used during winter months when burial was not an option. This explains the presence of fly pupae found during excavations of the graves and supports seasonality in burying (Gilbert and Bass,
1967) and/or secondary burial practices (Ubelaker and Willey, 1978), neither of which was thought to be an Arikara custom.

**The Archaeological Context**

Temporal patterning of artifacts, traditionally used to associate skeletal material to a particular archaeological phase, has proved to be less informative due to complex inter-tribal trading networks in the Northern Plains. Blakeslee (1975) suggests that the extensive trade network throughout the upper Missouri promoted cultural change and gene flow. The later sites and more peripheral areas provide craniometric evidence for gene flow, so there is not clear congruence between the archaeology and biology (Blakeslee, 1994). In the post-contact, Northern Plains, there is sufficient archaeological evidence to suggest ongoing conflicts and continuous political re-organization of tribes. The continual interactions between tribes through the inter-tribal trade network complicate tribal identification through grave goods and other materials associated with skeletal material. Despite these complications, the Larson Village Site (39WW2), along with the other sites around Mobridge, South Dakota, with the exception of the Sully Site, represent the northernmost extension of the Arikara prior to the reservation period.

Archaeological evidence indicates a long human occupation of the North and Central Plains. The Larson Cemetery (39WW2) is located near the town of Mobridge, South Dakota, in the Middle Missouri region of the Northern plains (Figure 2.1). This region is demarcated by the Nebraska-South Dakota border to the North Dakota-Montana border (Blakeslee, 1994). Three subdivisions within the Northern Plains are the Middle Missouri (Missouri River from the Nebraska-South Dakota border to the North Dakota-Montana border), Northwest Plains (west of
the Middle Missouri to the Rocky Mountains and northward to Canada), and the Northeastern Periphery (eastern North and South Dakota and western Minnesota).

The culture history of the region is generally divided into five broad periods: Paleo-Indian, Archaic, Woodland, Plains Village, and Historic (Wood, 1998; Zimmerman, 1985; Blakeslee, 1994). Differences in technology, subsistence strategies, settlement patterns, and socio-political organization define each of these periods. The periods roughly equate to temporal sequences defined by radiocarbon dating; however protohistoric and historic periods are not as well-defined as earlier periods, because of the exact timing of contact is not known, written documentation is rare, and there is considerable variation in the appearance of trade goods across the Northern Great Plains.

The Paleo-Indian period is represented by mobile bands of hunters and gatherers that followed big game herds. The Archaic period is characterized by nomadic foragers with a smaller range and an increasing adaption to local resources. The Woodland populations are marked by the development of horticulture and less nomadic life-ways. The river bottomlands contrasted the rest of the Plains ecology in flora and fauna, which led to the creation of two major groups: nomadic-hunting groups and river-based groups (Holder, 1970). The riverine groups, like the Arikara, Mandan, and Hidatsa tribes, lived in semi-permanent villages along the river course and practiced horticulture. This reliance on horticulture defines the Plains Village period. There is clear evidence for an increased importance of cultigens, such as maize, squash, sunflowers, and beans in the Plains Village period over that which is seen in the Woodland periods.
Figure 2.1. Geographical location of the Larson Site (39WW2), indicated by the red star.
Larson is located just southeast of the town of Mobridge, South Dakota.
In the Plains Village and historic periods there are three cultural traditions in the Northern Plains: Oneota, Middle Missouri, and Central Plains/Coalescent traditions. The Central Plains/Coalescent tradition appears to have led to the formation of the Pawnee and Arikara Tribes. The Central Plains derivation refers to sites south of the Nebraska-South Dakota border and ones that are dated prior to the protohistoric period; whereas the Coalescent tradition refers to all sites north of the border and are protohistoric or later. This area, where the Larson Site is located, is in the Middle Missouri region, which was occupied by the Arikara, Mandan, and Hidatsa tribes. The Plains Village had a Coalescent Tradition that was divided into three temporal variants: an Initial, Extended, and Post-contact. Some researchers have described a fourth “disorganized” phase, but this has now been accepted as part of the historic phase prior to the Reservation period (Lehmer, 1971). The initial coalescent variant (AD 1300-1600) is demarcated by intrusions of the Central Plains culture into South Dakota, which is suggested by an increase in warfare, a shift to circular house structure, and additions to the cultural traits. There is clear documentation, from archaeological patterns (Sigstad and Sigstad, 1973), craniometrics (Ubelaker and Jantz, 1979, Jantz, 1977), and language distribution (Parks, 1979), of a south-north migration by the ancestral Arikara in the Plains Village period (Blakeslee, 1994). The earliest sites that are suggested to represent the prehistoric antecedents to the Arikara are found in the Big Bend region and are attributed to the Initial Coalescent. These villages provide some of the first evidence in the region of widespread inter-tribal conflict as is indicated at the Crow Creek site [(39BF11), (Willey, 1990; Willey and Emerson, 1993)]. The Arikara continued a northward movement causing the displacement of the Middle Missouri people.
The Extended Coalescent variant (AD 1400/1450-1650) dominated much of the Missouri trench in South Dakota, but demonstrates a short occupational history (Lehmer, 1971). During the Extended Coalescent, the range of prehistoric Arikara extended to the Grand River. These sites are typically unfortified and widely spaced, but the northernmost settlements have more centralized fortified living area, which suggests a pushing of the Middle Missouri Tradition people northerly.

The Post-contact variant is indicated by the appearance of Euro-American items, even though direct contact did not occur until the mid-18th century. Currently, nine phases are recognized for the post-contact Coalescent: Felicia, Talking Crow, Bad River, Le Beau, Knife River, Willows, Minnetaree, Roadmaker, and Four Bears (Johnson, 1998). The phases attributed to the protohistoric Arikara are the Felicia, Talking Crow, Bad River, and Le Beau, based on house styles, fortifications, settlements patterns, artifact styles, and burial patterns (Johnson, 1998). The Larson Site (39WW2) is considered a protohistoric, postcontact, Le Beau Phase site (Lehmer, 1971; Lehmer and Caldwell, 1966) based on the presence of several circular earth lodges with associated ceramics, bone tools, shell, glass, and European goods. The Le Beau Phase sites are generally concentrated on the east bank of the Missouri River in the Grand-Moreau region.

**Dating of the Larson Village Site**

Several different dates have been suggested for the Larson Village Site. Owsley and Bass (1979) consider village occupation extending from 1751-1781 with complete village abandonment occurring simultaneous with a smallpox epidemic in 1981. According to Blakeslee
the association with the Le Beau cultural affiliation corresponds to approximately a 1679 to 1733 date. More recent research by Billeck and Dussubieux (2006), suggests an occupation of the site from 1700-1725 using glass trade beads. Their comparison of glass beads from the 17th, 18th, and 19th century Plains provides a very narrow date for the Arikara site. Johnson et al. (2007) provide the most comprehensive evaluation of the chronology of Middle Missouri Plains’ village sites to date. Using several conventional and AMS radiocarbon dates from short-lived materials, such as seeds and corn, and charred pot residue in conjunction with ceramic ordinations suggest that the Post-contact Coalescent cultural variant, of which the Larson Site is associated with, extended from 1650 to 1866. However, radiocarbon dating has a larger accompanying error, which accounts for the larger time interval. Mostly likely, the Arikara occupied the Larson Village in the early 1700s rather than the late 1700s as proposed by Owsley and Bass (1979). The change in the dating of the site plays a role into the interpretation of the village demographic composition. If the Larson Village represents an epidemic-based cemetery as has previously been hypothesized then the smallpox or other acute illness could have traveled to the village through the trade network rather than through direct Euro-American contact.

The Arikara

During the protohistoric time period, as defined by Holder (1970), there was known to be a long interaction between Europeans, Euro-Americans, and the Indian tribes of the Northern Plains, but little written documentation solidifying the interactions. Journals and various descriptions are found in the writings of Tabeau (Abel, 1932) and by Lewis and Clark in 1804, but due to the lack of other supporting documentation, archaeologists have deemed this period as
the “time in-between” prehistoric and historic, the protohistoric (Holder, 1970). Even though no written records corroborate it, direct contact between the Arikara and Europeans may have occurred as early as the 1700s (Ewers 1961). The long standing indirect contact between the Arikara and Europeans may have introduced disease prior to direct contact and could explain the subsequent depopulation epidemics associated with small-pox in the late 18th and early 19th century.

During the protohistoric time period, the Mandan and the Arikara villages served as large trading centers between the more nomadic tribes and the Europeans. Europeans added onto a pre-existing native trade network, which allowed for more extensive trade routes and eventually to direct trade. The Arikara provided a major source for bartering foodstuffs, like corn, pumpkins, native tobacco, and beans for material goods and meat. Arikara village occupation during this time was often short, since the length of the village occupation was related to the amount of arable land and wood available in the river bottoms (Ewers, 1961). Most villages were abandoned as site resources became depleted, usually in a span of 15-30 years (Holder 1970). The Larson Village is in line with this. The village midden deposits’ size and evidence of several rebuilding periods for the lodges, which are estimated to last seven to ten years based on ethnographic data, suggest a village occupation of approximately 30 years (Bowers, 1967). Owsley’s (1975) demographic analysis of the Larson Site supports the presence of a single generation.

The traditional native trade system was a direct exchange between the producer and the consumer (Ewers, 1961), involved perishable goods, and lasted well into the mid-1800s. With increasing European influence, the Arikara became middlemen in a complex trade exchange of
agricultural products, horses, guns, and other artifacts of European origin that extended over thousands of miles (Holder, 1970). Large villages along the Eastern Missouri River developed as is indicated by thick midden deposits. Each Arikara village was still a politically autonomous unit consisting of endogamous, matrilocal extended households (Holder, 1970). The development of distinct dialect formations in the pre-19th century villages provides evidence of inter-village isolation and low migration among Arikara. Pierre Tabeau recognized at least 10 dialectical divisions within the Arikara existing in 1804, which suggests a great diversity within the Arikara population alone (Ewers, 1961).

This transitional trade pattern, as is supported by the archaeological record, used European articles and non-perishable goods in the intertribal trade (Ewers, 1961). The European goods would make their way from the peripheral trading centers that had contact with the Europeans to the remote areas that did not have direct contact with the Europeans. The articles would consist of horses, riding gear, weapons, metal tools, clothing, and personal adornments. The Arikara’s geographic location placed them in an excellent position for trade, but the surplus of goods afforded to them, also made them targets for raids from other villages (Owsley et al., 1977). There is little record of the Arikara maintaining a surplus of European goods, such as horses and guns (Ewers, 1961). Rather, they traded them to other tribes.

As a result of growing competition and need in the fur trade, more European explorers went to the major tribal exchange centers. The river system provided the transportation means for European explorers to move west from the central valley (Holder, 1970; Rogers, 1990). This is most prominent in the late 1700s. The Europeans were met with great resistant as the Indians wanted to maintain the previous trading styles. This led to increasing intertribal conflicts and
European-Indian conflicts with little to show for it in return. Historical documents provide evidence for external pressure, hostilities, and intermittent warfare between the Arikara and other groups (Owsley et al., 1977), because most of the geographically isolated Arikara did not have the non-perishables that Europeans were wanting.

By the time Lewis and Clark visited the Arikara in the early 19th century, the Arikara experienced a severe reduction and concentration of the population. After the smallpox epidemic of 1780-1781, the Arikara traditional village pattern was disrupted (Lehmer and Jones, 1968). The population seemed to be at varying stages of flux at any given time depending on inter-tribal relationships, local resources, or relationships with European fur traders (Ewers, 1961). By 1832, the Arikara were all but removed from the Missouri River Valley because of tribal conflicts, European traders and settlers, and structured resettlements.

Mortality

The Larson Site represents a time period of increasing European influence on the Arikara. Prior to European exploration in South Dakota at least seven different Native American groups were known to have inhabited the area; including the Arikara, Hidatsa, and Mandan, who now comprise the Three Affiliated Tribes. All were considered horticultural tribes and belonged to an extensive trade network extending across much of the Plains. Westward expansion of Europeans in the late 17th and 18th centuries brought these tribes into ever-increasing contact with Euro-Americans. Verano and Ubelaker’s (1994) volume, Disease and Demography in the Americas, highlights the devastating effects that European contact had throughout North and South America, of which Owsley (1992) incorporated a demographic analysis of the prehistoric and
early historic population of the Northern Plains through a comparison of life table elements and independent age-at-death estimates, but only discussed disease in broad terms. A similar review can be found in Larsen and Milner (1993), which focused on the demographic and epidemiologic consequences of the European influx in the Americas and the Pacific. The edited volume, “Skeletal Biology in the Great Plains,” by Owsley and Jantz (1994), provided the coverage that was lacking in Larsen and Milner’s (1993) and Verano and Ubelaker’s (1994) volumes. However, this volume did not incorporate the methodological advances in their discussion of paleodemography, especially for the Protohistoric and Historic time periods. Williams (1994) provides a basic review of some demographic parameters of the Archaic and Woodland populations, but little else is detailed. Demographic profiles for Mobridge (39WW1) (Palkovich, 1981) and Larson (39WW2) (Owsley and Bass, 1979) are available, but warrant a re-examination to incorporate the recent theoretical and methodological advancements in paleodemography. The incorporation of hazard analyses may increase our understanding of how health and mortality were affected by the Westward expansion of Europeans. There is a need for the integration of biological and cultural information when addressing the demographic and social consequences of contact (Milner, 1998). Several confounding factors cause socio-cultural changes within the Upper Plains, which are highlighted in Owsley and Jantz (1994), but are examined in isolation from one another. Most literature now dismisses the views of Dobyns (1983) that newly introduced high-mortality diseases spread frequently and essentially uniformly across the North American continent. If European contact did not cause a rapid demographic collapse as some have theorized, then the differential in risk of death between Native American tribes and the complex socio-cultural schemes of these tribes and how they buffered the effects
of European contact need to be addressed (Milner, 1992; Johansson and Owsley, 2002). Nonetheless, outbreaks of disease became frequent after the arrival of Europeans in the late 15th century. Consensus exists that contact-induced infectious disease contributed to the decline of Native American populations. According to Warrick (2003) archaeological settlement data and historic documentation provide clear evidence for the “crisis” mortality seen in Natives in the Northeastern United States. Warrick (2003) indicates a delay between initial colonization and spread of disease occurred. Snow and Lanphear (1988) noted that most diseases did not occur until several years after first direct contact and that the geographical and cultural boundaries would have buffered and/or guided the spread of disease.

Owsley’s examination of the Larson population’s mortality, survivorship, age-specific probability of death, and life expectancy is the only demographic analysis of the protohistoric Arikara thought to have inhabited the Larson Village, ca. 1750-1781 (Owsley and Bass, 1979). Several researchers have added to his analysis by examining specific disease processes and suggesting these as the potential cause to the mortality pattern suggested by Owsley and Bass (1979). They suggested that the Larson Village had a high infant mortality rate that remained high throughout childhood, low adolescent mortality, and maximum mortality between 35 to 39 years of age with a total population between 430 and 560 individuals. Also, only 1.9% of the population lived past 35 years with a crude death rate of 70 per 1000. Furthermore, a disproportionate mortality rate between the sexes existed, in which young adult females had a greater risk of death (Owsley and Bradtmiller, 1983). When compared to model life tables (Weiss 1973), the mortality pattern was not significantly different than expected for pre-industrial populations. Nevertheless, several reasons were suggested to explain the high
mortality rate and youthfulness of the cemetery sample, including famine, increased intertribal warfare, complications from childbirth, and an increased prevalence of communicable diseases. These were also suggested as the causes for the mortality profile of the Leavenworth site, ca. 1803-1835, analyzed by Bass et al., (1971). Bass et al. (1971) suggested the historic Arikara population at Leavenworth was in decline from increasing conflicts, disease, and European encroachment. Whereas the Leavenworth site has clear historical documentation to support a population in decline, the Larson Site does not. In particular, Owsley (1975) suggested the Larson Site supports the smallpox epidemic of 1780-1781 as a source for the individuals within the cemetery and provides evidence of tuberculosis in at least 11 juvenile and adult skeletons. The skeletal involvement associated with tuberculosis could also be the result of a fungal infection, blastomycosis. Palkovich (1981) examined the two-components of the Mobridge Site and believed that differential mortality was apparent between the components and used several skeletal indicators to explain the mortality profile, where Mobridge Two exhibits expected patterns to a stable population and Mobridge One has several age-related spikes. Palkovich (1981) and Kelley and Eisenberg (1987) believe that some of the Arikara skeletons from Mobridge have manifestations of blastomycosis instead of, or simultaneous with, tuberculosis rather than just tuberculosis. South Dakota is one of the areas in which blastomycosis is endemic, but does not have large numbers of cases annually like that which is seen in the Ohio and Mississippi River valleys. Several skeletons within the Larson Site demonstrate a similar pattern of skeletal lesions as that seen in Mobridge, including juveniles.

The Larson Site is also unique in that skeletons were recovered from a well-defined cemetery as well as on the floor of the earth lodges. Both areas were incorporated into the
demographic analysis of the Larson Site by Owsley and Bass (1979). Subsequently, Johansson and Owsley (2002) have indicated that these portions should not be evaluated as one. Most individuals recovered from the village proper were commingled and displayed evidence of trauma (Owsley et al., 1977). This research, which is evaluating the mortality of the population, does not include the skeletal remains recovered from the lodge floors at the Larson Village even though they may represent a single breeding population.

Owsley et al. (1977, 1994) have indicated that the presence of the individuals in the village proper, the trauma visible on the skeletons, and the demographic composition of the individual remains support the ethnohistoric accounts suggesting an increasing amount of conflict in the post-contact period. There is sufficient archaeological evidence to suggest ongoing conflicts and continuous political re-organization of tribes and historical documents provide good evidence for external pressure, hostilities, and intermittent warfare between the Arikara and other groups (Owsley et al., 1977). Increasing intertribal conflict to maintain control of the trade networks, the westward advancement of traders, and growing competition for resources caused a horticultural based tribe to become increasingly mobile and abandon villages quickly. The instability of the population structure and the advent of infectious disease epidemics caused severe population loss (Owsley, 1994). In 1700, the estimated numbers of Arikara were thought to have been approximately 15,000 with 4,000 warriors. By 1785, 7 villages and 900 warriors represented the Arikara, and by 1809 the number of Arikara in and along the Missouri River is estimated at a total of 2,600 individuals. It is believed that the Smallpox pandemic, 1780-1781, caused 50 to 75% of the Arikara to perish.
Summary

The Arikara have a long history in the Middle Missouri River Basin, which was drastically changed as a result of an increasing European presence in the 1700s. During this post-contact period, several factors affected the health, demography, nutrition, and sociocultural structure; including the introduction of acute illness such as smallpox, the acquisition of the horse, and increased European presence (Holder, 1970). Also, the Arikara experienced an increasing pressure from the migration of tribes into the Missouri Valley and experienced an increased competition for resources. The diversity of the people and the outside pressures experienced by the Arikara provide an excellent basis for comparative research on the health and mortality changes caused by contact with Euro-Americans. The incorporation of statistical models that can integrate both health indicators and demographic parameters gleaned from the bone have the potential to create new, independent tests of the archaeological and historically derived hypotheses.
Paleodemography, the study of population dynamics, evaluates how mortality, fertility, and migration are affected by the bio-cultural and socio-political landscape within and between populations. As such, it has been used to highlight major demographic transitions caused by micro- and macro-evolutionary processes throughout human history, because population change leaves characteristic signatures in the gene pool. The basis for comparisons rests on determining if the estimated mortality profile departs from known extant age structures in conjunction with evidence as to the specific cultural and biological processes biasing the demographic structure.

One of the major goals in paleodemographic analyses is to determine the mortality profile of a population and investigate its plausibility compared to known human demographic patterns. Bioarchaeologists have used divergence from known demographic patterns to hypothesize as to the biocultural and/or taphonomic underpinnings causing these inconsistencies. Contemporary human populations follow regular patterns of mortality (Paine, 2000; Coale and Demeny, 1983). Unfortunately, skeletal populations often exhibit different patterns than the known, which has led to questioning our ability to make interpretations (Paine, 2000). A recurring question in paleodemography is if it is possible to accurately estimate mortality, fertility, and population dynamics from bioarchaeological data (Gage, 2010). Demography is primarily concerned with age-specific mortality and fertility and relies on quality census data that are unbiased in the enumeration of births and deaths, which is infeasible for most archaeological populations. Instead of directly estimating demographic parameters, indirect approaches that rely on age at death statistics have been used in paleodemography (Gage, 2010). Reconstructions of mortality
patterns, length of cemetery use, and life expectancy have been a major part of bioarchaeological analyses since the early 20\textsuperscript{th} century; but the application of, methodological basis for, and interpretation of paleodemographic results have been inconsistent (Frankenberg and Konigsberg, 2006; Konigsberg and Frankenberg, 2013).

A Brief History

Hooton’s (1920, 1930) work represents an early application of paleodemography and focused on estimation of population size and length of cemetery use, but his analyses have since been deemed incomplete (Frankenberg and Konigsberg, 2006). Angel (1969) called for a more comprehensive approach that integrated both physical anthropologists and archaeologists to understand the population dynamics of a skeletal population. The years following Angel (1969) saw major advances in demographic theory (Peterson 1975), but little methodological development beyond tabulations of age at death intervals and graphical representation of different age-at-death distributions (Paine, 2000; Konigsberg and Frankenberg, 2013). Abridged life tables were the main product of paleodemographers of the 1970s. Acsadi and Nemeskeri’s *History of Human Lifespan and Mortality* (1971) demonstrated through the application of life tables that an increase in life expectancy corresponded with the adoption of agriculture. This was followed by several others, who incorporated life tables within their bioarchaeological analyses (Weiss, 1973; Moore *et al.*, 1975; Swedlund and Armelagos, 1976). Life tables provided an improvement over the then available methods, but did not solve the methodological problems with age estimation or the lack of demographic tools being applied in analyses. It was not until the early 1980s that major criticisms of the field (Bocquet-Appel and Masset, 1982;
Howell, 1982; Sattenspiel and Harpending, 1983; VanGerven and Armelagos, 1983) encouraged major theoretical and methodological improvements (Armelagos and VanGerven, 2003; Boldsen, 1988; Gage, 1988, 1989; Paine, 1989; Konigsberg and Frankenberg, 1992, 1994; Wood et al., 1992a, b). Significant improvements included both age estimation techniques and model estimation. Konigsberg and Frankenberg (1992) suggested the use of contingency table demography to alleviate some of the issues found with abridged life tables with similar approaches suggested by Bocquet-Appel and Masset (1996). However, Konigsberg and Frankenberg (2002) clearly state that contingency tables do not provide a major improvement over abridged life tables. Rather, they are just as susceptible to overfitting, as demonstrated by Jackes (2000). Jackes (2000) produced more age classes than indicator states, which prevented model construction. Hoppa and Vaupel’s (2002) volume summarizes much of these advancements and demonstrate how paleodemography has become a standard in bioarchaeological analyses. The questions that remain are how to best integrate data from multiple age indicators into a model for the age-at-death distribution and how can skeletal indicators of health be easily combined with an age distribution to improve interpretations?

Several theoretical and methodological issues exist that affect the efficacy of paleodemographic profiles and any subsequent interpretations including: sample biases, errors in age estimation methods (see the following chapter), capturing non-stationarity within a population, and dealing with selective mortality and the heterogeneity in the risk of death (Buikstra and Beck, 2006). A correlate to the site formation processes outlined by Binford and Bertram (1977), are the sample formation processes associated with skeletal assemblages (Milner et al., 2008): 1) the living individuals for which demographic parameters are based; 2) the
individuals that died—whether their death was associated with selective mortality or hidden heterogeneity in death or other unknown risks of death; 3) the individuals actually buried as determined by cultural practices; 4) the number of individuals preserved over time in relation to taphonomic conditions; 5) the quality and quantity of recovery; and 6) the amount of material curated. After consideration of these factors and when appropriate data and methods of analysis are available, hypotheses can be made about population dynamics (Paine, 2000; Bonneuil, 2005; Chamberlain, 2006); even though some have disregarded paleodemography’s ability to generate any hypotheses at all (Lovejoy et al., 1977).

**Sample Bias**

Skeletal samples represent one of the only means to evaluate mortality in prehistoric populations. A mortality sample is a highly selected sample of the people at a particular age who were once living, because of selective mortality and heterogeneity in frailty among the living, preservation of the skeletal material, and the excavation and curation of the recovered materials (Wood et al., 1992a). Representativeness of a sample tends to be acknowledged and then assumed in population-based analyses, because it is difficult to address if a bias exists and if so why (Hoppa, 1996). The ideal for population-based studies is that the skeletal sample being used has a one-to-one relationship to the population from which it is derived, which means that no biases exist. Unfortunately, this is not reality. Several researchers have acknowledged possible biases, which can alter the composition of the skeletal sample, including cultural practices, biological status, taphonomic destruction, or excavation practices (Gordon and Buikstra, 1981; Waldron, 1987; Walker et al., 1988; Jackes, 1992; Nawrocki, 1995; Guy et al., 1997; Hoppa and
Saunders, 1998). These biases have the potential to drastically affect mortality curves, which limits the scope of any demographic inferences derived from them, but does not negate their construction (Alesan et al., 1999; Jones and Ubelaker, 2001).

The only consideration that would suggest a systematic bias is that the estimation of population size from the historic Arikara village, Leavenworth (39CO9), indicated the presence of at least one additional cemetery (Bass et al., 1971). However, site surveys did not indicate any additional cemeteries within the area of the Larson Village (Bass and Rucker, 1976). Also, ethnographic and archaeological data support the assumption that one population of Arikara Indians utilized the Larson Site cemetery to the exclusion of any other burial locations. Additionally, comparison with other Arikara sites does not indicate differential burial practices. Differential burial practices have been considered a major contributor to sample biases. However, historic and ethnographic data indicate that the Arikara did not practice differential burial practices during the protohistoric time period. A few prehistoric Woodland sites have infant burials associated with house floors, but this does not seem to be a continued practice within the protohistoric period. Also, a portion of the villagers left for long stretches of time for trading purposes, which was intensified during the protohistoric period when resources were becoming scarce with the increase in settlers and other Indian tribes within the Missouri River Basin (Ewers, 1961). Prior to the entire village becoming more nomadic, it is believed that a large portion of the village occupants, adult men and women, left for long periods of time for hunting and trading purposes, which would leave the elderly and very young in the village (Ewers, 1961). Thus, the cemetery should reflect higher numbers of the very young and the very old, two groups typically having a greater risk of death.
As early as Johnston and Snow (1961) and Johnston (1968), literature acknowledges the difficulties resulting from a lack of juveniles in a skeletal sample. Paine and Harpending (1998) suggest the lack of young decreases fertility estimates in a population; whereas, the lack of the old inflates the crude birth rate. The under-enumeration of juvenile skeletons in archaeological samples, especially infants, questions our ability to study population dynamics. Moore et al. (1975) demonstrated how infant under-enumeration significantly impacted life table parameter estimates relating to life expectancy at birth and Pennington (1996) noted that representative cemetery samples with large amount of sub-adults, particularly infants, can impact age-specific survivorship and the subsequent life table parameters, including mean age-at-death. Walker et al.’s (1988) comparison of 19th century La Purisima mission records to excavation records provides further evidence of the issue of preservation of juvenile remains causing an under-enumeration of young children. The mission records indicate a high number of infants and elderly should be in the cemetery, but during excavation more young adults than infants were recovered. Similarly, Jones and Ubelaker (2001) noted a significant difference between the hypothesized number of infants in the Voegtly cemetery, Pittsburgh Pennsylvania from the historical documents compared to the excavation reports. They excavated only 50% of the infants hypothesized to be in the cemetery according to the records. Guy et al. (1997) suggest that the fragility, bone density, and lack of cortical bone in infant remains cause them to be more susceptible to taphonomic forces. The high organic to inorganic component in immature bone significantly affects its preservation. Erosion and changing of water levels during the excavations of the Larson Village could have caused an additional loss of infants as the field records document several burials being excavated under several inches of water. However, over
half of the Larson Village cemetery sample is juvenile with a large portion of these being less than 1 year of age. Guy et al. (1997) suggest that infants under one should comprise 25% of a pre-industrial population, but in reality infants only comprised 5-6% of the total skeletal sample in their research. Nearly one-third of the Larson Cemetery is infants under the age of one, which is closer to the expected percentage of subadults when compared to the historical demographic records. The composition of the Larson Site makes it an ideal sample to study protohistoric population dynamics.

Additionally, a skeletal sample is assumed to represent a breeding population for demography purposes, as this is a fundamental assumption to demographic analyses (Alesan et al., 1999). For example, Indian Knoll represents a cemetery in use for 500+ years (Howell, 1976), which makes it unlikely that it represented a single interbreeding population. Archaeological data from the River Basin surveys (Lehmer, 1971) and prior demographic analyses suggest a 30 year use of the cemetery, which correlates with a typical village occupation period (Owsley, 1975; Owsley et al., 1977; Owsley and Bass, 1979).

Peterson (1975) argues skeletal sample sizes are so small that they do not represent any real population, and research has demonstrated that sample sizes of 100 plus are preferred, because parameters become more difficult to recover in small samples sizes (Hoppa and Saunders, 1998; Usher, 2000). The limited size of a sample can be mitigated through the application of the appropriate statistical tests, but the composition and any associated biases cannot. Hence, the number of skeletal remains recovered during excavation and the quality of the preservation impact the quality of any demographic inferences. Even though the field staff had to contend with rising water levels, the trained excavation personnel and systematic
excavation practices provided a very well-preserved skeletal assemblage in which there are a large number of juvenile skeletons. Bass (1981) estimated at least 90 percent of the skeletons within the cemetery were recovered with most of those recovered having excellent bone preservation.

**Selective Mortality**

A mortality sample is inherently biased by the fact that it represents only a small portion of the once living population. Selective mortality refers to the fact that the skeletal sample under study is a highly selected sample of the dead rather than a sample of all the living individuals who were at risk of death at a given age (Wood *et al.* 1992a). Individuals have different experiences of health and illness, and it is this history that contributes to their entry into the skeletal assemblage at a given age. As a result, issues of heterogeneity in the risk of death must be addressed in paleodemographic research, as well. A cemetery is not going to have all the individuals that died or be a random sample of all who were alive in a given age interval. All skeletal samples are under-representative of the original living population at risk of death. The shape of the hazard function is going to be impacted by the selection process, which is the individual age-specific frailty. Owsley and Bass (1979) and Owsley and Bradtmiller (1983) indicate selective mortality between the sexes in which females had a higher risk of death in early adulthood. Others have indicated sex-based differential mortality in Mississippian period skeletal material (Wilson and Steadman, 2008) and Medieval Black Death individuals (Redfern and DeWitte, 2011), but little Native American data is available for direct comparison with the Larson Site. Overall issues of selective mortality have been well demonstrated in
paleodemographic analysis (Usher, 2000; Boldsen, 2005; Boldsen, 2007). Recent work on the Black Death (Dewitte and Wood, 2008; DeWitte, 2009; Redfern and DeWitte, 2011) indicates that mortality was selective, which lends credence to the idea that selectivity can be gleaned from the skeletal data.

**Hidden Heterogeneity**

Hidden heterogeneity is correlated to the issue of selective mortality in that the skeletal sample is comprised of an unknown mixture of individuals who varied in their underlying frailty. Both heterogeneity and selective mortality confound interpretations of morbidity and mortality, because the skeletal sample are the non-survivors. Individual frailty, the individual’s risk compared to the cohort risk, is a product of the individual’s susceptibility or relative risk with respect to disease or death (Wood et al., 1992a). When hidden heterogeneity is not accounted for in model construction the aggregate levels of mortality can be misleading. For example the overall adult mortality, which includes both the male and females, indicates a mortality pattern that may differ from the individual male and female mortality patterns.

Cohen (1994) argued that heterogeneity in pre-industrial populations does not significantly affect model building, because these populations do not have the hierarchical structure, so it could be assumed that all individuals within the population have an equal risk of death. Cohen (1994) assumed that only stratified populations could have differential mortality due to unequal access to resources. However, even non-human species of animals display selective mortality, because not all individuals that acquire a disease will die from that disease.
Non-stationarity

Stationarity is often assumed in paleodemography, because it allows for estimation of mortality rates for past populations from skeletal age-at-death distributions. A stationary population is a population that is closed to migration, has a constant age-specific fertility and mortality rate, and a zero growth rate; whereas, a stable population does not assume a zero growth rate. In a stationary population, the mortality and fertility are constant and the population is not growing or declining. The concept of a stationary population stems from the idea that population growth has been around zero for much of human existence (Alesan et al., 1999). Molecular studies have demonstrated that the human population was very small prior to 50,000 to 100,000 B.P., which implies a very low growth rate (Premo and Hublin, 2009). Thus the stability of the human population has served as the basis for the assumption of stationarity in paleodemography. As such, it is assumed that the individual ages are known and can be assigned to discrete age intervals for a skeletal sample, but this does not account for the state of the once living population that may have been growing or declining (Moore et al., 1975).

If a population is not stationary the age-at-death distribution can be distorted and biased estimates of the age distribution and mortality produced (Sattenspiel and Harpending, 1983; Johansson and Horowitz, 1986). Hence, changes in population growth can significantly impact demographic interpretations. Frankenberg and Konigsberg (2006: 244, Figure 6) illustrate that survivorship will be overestimated in a declining population when there is an incorrect assumption of
stationarity. Conversely, survivorship can appear to be reduced in a growing population when there is an assumption of stationarity (Sattenspiel and Harpending, 1982; Milner et al., 2000). Small variations in fertility significantly affect age-at-death distributions; while large modifications to mortality do not have the same impact. Two populations with identical age-at-death distributions can exist and have different fertility rates. For example, a large portion of children within a skeletal sample may be used to suggest a growing population; however, a large portion of children also reduces the average age-at-death for the entire skeletal sample. A smaller number of children, especially as a result of under-enumeration, can lead to over-estimation of the average age-at-death (Horowitz et al., 1998; Milner et al., 2000). This issue has led to the argument that age-at-death distribution changes reflect fertility more than mortality (Sattenspiel and Harpending, 1983; Johansson and Horowitz, 1986). Sattenspiel and Harpending (1983) indicate that the age-at-death distributions tells us more about fertility than mortality if the growth rate is assumed to be zero when it is not. The fact that the growth rate is unknown for most populations is a major issue in paleodemographic analyses of prehistoric populations and has been reiterated with many resolutions being suggested (Johansson and Horowitz, 1986; Buikstra et al., 1986; Gage, 1988; Paine, 1989). Regardless of the debate, if population growth is not accounted for a population may be considered to be experiencing increased mortality. Therefore, it is better to assume population stability (Wood et al., 2002). A stable population is when the fertility and mortality rate are constant and net migration is zero for all ages (Lotka, 1922).
Uniformitarianism

The underlining premise to all paleodemography is uniformitarianism. The uniformitarian basis acknowledges no difference in fertility, maturation, or senescence between populations over time and space. Howell (1976: 26) succinctly defined this position by stating “humans have not changed in the processes by which they respond to environmental fluctuations because certain aspects of human life-history are subject to evolutionary constraints, like reproductive maturation and menopause.” The ability to respond to environmental changes may vary between populations, but the demographic processes do not; making it possible to model these processes.

Several have argued that age patterns depart from the expected model data (Meindl and Russel, 1998) where the survival curve contrasts with modern populations (Mensforth, 1990). Howell’s (1982) re-analysis of the Libben sample demonstrated that the life table that Lovejoy et al. (1977) constructed for Libben is atypical when compared to known human demography patterns. Thus, the Libben population either significantly differs from known modern or the age-at-death estimates that served as the basis for the modeling of the population are questionable. It challenges hypothesis testing, especially regarding the major demographic transitions in human history, because we know that people are not the same, but in order to use standards developed from modern material to age prehistoric skeletons we must assume that the aging process is the same (Aykroyd et al., 1996; Aykroyd et al., 1997, Hoppa, 2002; Frankenberg and Konigsberg, 2006). Accepting an uniformitarian approach and believing that variation in fertility and mortality is predictable allows for the patterns of age-specific fertility and mortality to be modeled (Coale and Demeny, 1983). Although uniformitarianism is a major problem in the application of age-at-death estimation methods assuming senescence is uniform prior to model
building helps determine how well a population responded to environmental influences, which is the ultimate goal. The uniformitarian assumption has two primary implications for paleodemography 1) if one assumes the biological response of humans to the environment is constant, researchers are able to think about how mortality profiles are impacted by the environment in etiological ways and 2) if the socio-cultural or biological component of the environment is the only variable changing over time then it must be related to the observed differences in mortality profiles between populations (Hoppa, 2002). Thus, by assuming the underlying demographic processes are the same across human populations, prehistoric populations should not deviate significantly from known modern populations.

**Modeling**

Several methods for modeling mortality have been proposed over the years in hopes to reconstruct demographic/mortality patterns, length of cemetery use, and life expectancy, but the application and estimation of these have been inconsistent in anthropological literature (Frankenberg and Konigsberg, 2006). The mid-20th century was dominated by approaches that tabulated and graphically displayed distributions of different skeletal samples. By the 1970’s the abridged life table was the major method of modeling and interpretation mortality. More recently, survival analysis had become a major method of understanding population structure and change. All of these methods rely on the interpretation of the results from ethnographic, historical, and archaeological documentation and comparison with known extinct and extant small-scale societies.

Abridged life tables have been the predominant method to create mortality profiles from cumulative age-at-death estimates for a skeletal sample and is still consistently found in the
anthropological literature (Acsadi and Nemeskeri, 1970; Ubelaker, 1974; Swedlund and Armelagos, 1976; Lovejoy et al., 1977); even though anthropologists were trying to understand population dynamics well before the common use of life tables in the 1970s (Frankenberg and Konigsberg, 2006). Life tables provide anthropologists a means by which to make demographic inferences and are relatively easy to produce. A life table is the summed number of deaths within various age categories, which is used to compute life expectancy per age category, the probability of death within each category, and the overall age structure of the once living population. Thus, paleodemographers construct life tables based on age-at-death data to estimate age-specific mortality rates, average age of death, and to make inferences about the level of health and quality of life. Weiss (1973) developed empirical life tables for anthropological populations. Owsley and colleagues (Owsley, 1975; Owsley et al., 1977; Owsley and Bass, 1979) followed much of what Angel considered vital statistics (1969) to study the demography of the Larson Site, including reconstruction of the age composition, mortality at different periods of life, adult longevity of each sex, and sex ratios of adults using model life tables as a source for comparison.

Life table use in paleodemography has been heavily criticized for the assumptions and data required to produce informative tables (Sattenspiel and Harpending, 1983; Konigsberg and Frankenberg, 1992, 1994; Milner et al., 2000). Life tables are restrictive in the types of data that can be used and the number of analyses that can be accomplished from them, because they require conforming to an age pattern of mortality (Gage 1988). This can lead to the wrong mortality pattern being applied to a population if the population being modeled diverges significantly from known demographic patterns. Also, the number of deaths for each age
interval is not known, the ages are estimated, and often there is an erroneous assumption of stationarity (Konigsberg and Frankenberg, 1992; Sattenspiel and Harpending, 1983; Johansson and Horowitz, 1986). This is based on the belief of a stable population where populations will typically re-establish the modal age structure within a few decades of a demographic disturbance (Weiss, 1973). Researchers have suggested calculations to account for the growth and decline of a population within the life table structure, but most research has assumed a zero population growth rate. Also, because of the issue of under-enumeration of infants, many researchers do not include the very young in life tables because it can drastically shift a survivorship curve (Moore et al., 1975). Furthermore, over parameterization often occurs in model building (Jackes, 2000), where there are more age categories than age indicators in a life table (Konigsberg and Frankenberg, 2002). The lumping of age ranges assumes an equal exposure to the risk of death, even though an individual skeleton has its own inherent risk based on the available skeletal traits (Wood et al., 1992b). Finally, it is nearly impossible to address issues of frailty or well-being in a sound statistical approach using life tables because of the age lumping.

Life tables are not the preferred method for constructing a mortality profile for several theoretical and methodological reasons. The age estimation techniques used to produce life tables were problematic and the demographic methods based in census and historical data were not easily applied to skeletal samples (Bocquet-Appel and Masset, 1982; Howell, 1982; Sattenspiel and Harpending, 1983, Buikstra and Konigsberg, 1985). Also, the quality of data used to construct Weiss’ empirical tables has been questioned.

Hazard models have been suggested as an alternative to life table models (Wood et al., 1992b; Gage, 1988; Gage and Dyke, 1986; Milner et al., 2000; Hoppa and Vaupel, 2002). Since
the variation in mortality patterns between pre-industrial and small-scale populations is quite similar, overall generalizations can be made about the age-specific risk of death (Gurven and Kaplan, 2007). Also, hazard models optimize the parameters for age-specific mortality rates based on the skeletal data, they are not limited as to the number of parameters as life tables, and can incorporate any variables deemed as contributing to the hazard rate including confounding effects of demographic non-stationarity and instability (Frankenberg and Konigsberg, 2006). As such, hazard models provide researchers the ability to investigate the dynamic demographic processes that create the mortality profile. Also, hazard models allow for the age-at-death patterns to be directly fitted to survivorship, death rate, and age structure data (Hoppa, 2002).

Hazard models have practically replaced the contingency table, non-parametric approaches in paleodemographic survival analyses that predominated in the 1970s and 1980s (Frankenberg and Konigsberg, 2006). Hazard models have been used in demography, epidemiology, and in industrial sciences to understand the risk of events that vary continuously with time using relatively few parameters, because they can smooth and improve data without imposing a particular pattern of mortality (Eshed et al., 2004; Gage, 2010). Also, they reduce the number of parameters relative to the age cohorts, so they are useful when little data is available. Hazards analysis provides a way to deal with differing age ranges that could be assigned to an individual (e.g.; 50+, 15-25, or 20 to 60 years old at the time of death) as interval censored data so that each skeleton could have a different age interval length (Frankenberg and Konigsberg, 2006). Also, hazards analysis allows for estimates of mortality for all ages, even though precise age estimates for all ages are not known (Milner et al., 2000).
Hazard models do not impose a fixed age pattern to the data; instead, the data determines the age pattern (Gage, 1988). Therefore, when a dataset is of sufficient quantity and quality, hazard models can provide an improvement over that of model life tables. Parametric hazard models tend to be used, because they smooth data when sample sizes or mortality data are inadequate (Eshed et al., 2004).

Regardless of the type of hazard model applied, the models are used to determine the age-specific forces (hazard) of mortality ($\mu(a)$), the survival function ($S(a)$), and the probability density function ($f_0(a)$). In a traditional demographic life table one estimate the age-specific probability of death ($q_x$), while in hazard models ones estimates the instantaneous hazard rate. The rate can be greater than 1.0, while the $q_x$ in the life table cannot (Wood et al., 2002). The survivorship is the proportion of the original birth cohort surviving to a given age. This is equivalent to the $l(x)$ in the life table. The probability density function is a smoothing function representing the age-specific probability of death in a particular age category.

The force of mortality or risk of death ($\mu(a)$), provides an age-specific mortality rate. Typically, the force of mortality is high during infancy, declines to its lowest point in childhood and young adulthood, and significantly increases during older adulthood. The survival function ($S(a)$) specifies the probability of an individual surviving to a particular age. It is assumed that the survival function is 1.0 at birth and declines until it approaches zero with senility. The survival function informs researchers on the mortality patterns within and between skeletal samples; hence, it is used heavily for hypothesis construction and interpretation because it is the proportion of a cohort starting at time zero that is still alive at time $a$. The probability density function ($f_0(a)$) approximates a mortality distribution at a particular population growth rate,
which is usually assumed to be zero (Wood et al., 2002; Milner et al., 2008). It is a fraction of all deaths from the initial cohort that are likely to die at a specific point in time.

The selection of the appropriate model is inherent to analyses, so the model that best fits the data structure should be used. Several goodness-of-fit tests are available to compare hazard models. Parametric hazard models are more commonly used because they smooth the data, especially when sample size is small or mortality data is inadequate, which is typical in bioarchaeology (Eshed et al., 2004; Frankenberg and Konigsberg, 2006).

The Gompertz model was the first parametric model to be developed to model human mortality and is a direct reflection of the attritional mortality with senescence (Gompertz, 1825). The Gompertz hazard function can be written as:

$$\mu(a) = \alpha e^{\beta a},$$

where the two parameters ($\alpha$ and $\beta$) are estimated via optimization, usually in the form of a maximum likelihood estimator using a computer algorithm. It is important to note that the numbering convention used here and throughout this researcher follows that of the Siler model (Siler 1979). The $\alpha$ parameter determines the overall level of adult mortality, while the $\beta$ reflects how the risk of death accelerates with age (Wood et al., 2002). The risk of death is proportional to the remaining physiological capacity of an individual (Gage, 1989). The Gompertz model is commonly used in industry to determine the failure rates associated with use of equipment, but is useful to examine the age-dependent component (adults) of a population in paleodemography. Since a juvenile component risk of death generally decreases with age, it is not appropriate to fit
a Gompertz model to a sample with juveniles, but the inverse or negative Gompertz can be used to model juvenile mortality.

The Gompertz-Makeham hazard model is a modified Gompertz hazard model and can be written as:

\[ \mu(a) = \alpha_3 e^{\beta_3 a} + \alpha_2. \]

where a third, constant parameter (\(\alpha_2\)), the age-independent component accounts for the deaths within a skeletal sample that are not captured by the exponential age-dependent, Gompertz parameter (Makeham, 1860). This parameter is often excluded from paleodemographic analyses, because it is difficult to estimate accurately from skeletal data and is deemed negligible compared to the other parameter estimates (Herrmann and Konigsberg, 2002).

The Gompertz-Makeham model helps explain causes of death (competing hazards) that are independent of each other or age, such as disease, accidents, or warfare. Previous research has indicated it is a useful tool if differential mortality within the sexes is suspected in a population (Wilson and Steadman 2008). Owsley and Bass (1979) report a high number of young adult females in the Larson Cemetery, which he attributed to the hazards of childbearing. Wilson and Steadman (2008) found a similar pattern of a large number of young-adult females in the Mississippian-period Orendorf Cemetery and determined that the combined Gompertz-Makeham model fit better than just the Gompertz. The Gompertz-Makeham was able to capture the independent risk of death for females, which may have affected frailty and well-being of the
population. However, like the Gompertz model, this model does not account for the juvenile component in the cemetery.

In order to adequately accommodate the juvenile component in hazard analyses without being too complex, the Siler (1979) model is typically employed. The Siler (1979) model has been proven useful for understanding the entire mortality profile of a population, because it divides mortality into three competing components: a juvenile, adult, and age-independent component. The hazard for the Siler model can be written as:

\[ \mu(a) = \alpha_1 e^{-\beta_1 a} + \alpha_2 + \alpha_3 e^{\beta_3 a}, \]

where \( \alpha_1 \) and \( \beta_1 \) parameters are added into the pre-existing Gompertz-Makeham model as a negative Gompertz component. Gage (1990) indicates it is the most parsimonious model for explaining human mortality. Also Gage and colleagues (Gage 1988, 1989, 1990; Gage and O’Connor, 1994) have demonstrated the utility of the Siler model for explaining both human and non-human population dynamics that fits the mortality pattern for the entire lifespan of a population (Gage, 1990). O’Connor et al. (1997) and more recently (Nagaoka et al. 2006) have used the Siler as the primary method of analysis. The Siler model is a parametric competing hazard model that allows for the integration of juvenile data, which in many cases when omitted will provide an overestimated expectation of life (Gage, 2005). Gage (1990) demonstrated that the Siler model fit a wider range of mortality patterns than the Coale-Demeny (1983) model life tables and O’Connor (1995) showed that it could be fit to any of the patterns in the paleodemographic literature. The Siler model has three competing hazards: a juvenile
component, an age-independent component, and a senescent Gompertz component. The juvenile component, which is a negative Gompertz, is comprised of two parameters ($\alpha_1$ and $\beta_2$) that capture the generalized infant mortality and the decreasing risk of death with age; whereas, the age-independent component ($\alpha_2$) and Gompertz ($\alpha_3$ and $\beta_3$) components are identical to those previously discussed.

Like the Gompertz-Makeham model, each hazard is assumed to be independent (Wood et al., 2002). Gage (1989, 1991) has demonstrated that the three competing hazards mirror mortality patterns well, but criticisms on the interpretive capabilities for the juvenile component have been questioned (O’Connor, 1995). However, it is useful in pre-industrial cemetery populations that contain a high proportion of juveniles (O’Connor, 1995). The age-independent component, is often assumed to be negligible and removed from the model (Herrmann and Konigsberg 2002) leaving a four parameter Siler model.

A few issues arise with the implementation of these three parametric hazard models. The Gompertz, Gompertz-Makeham, and Siler models all assume equal levels of frailty for the population. It is assumed that everyone is at equal risk of dying from age-independent factors, which does not account for selective mortality (Wood et al., 1992a; Milner et al., 2000; Boldsen, 2007). Some researchers have proposed alternatives to the Gompertz, Gompertz-Makeham, and Siler models that include multi-state, mixed, or nested hazard models. For example, adding a “frailty” component allows for sub-groups within a population, such as those associated with class or gender to have different age-independent hazard rates while having equal senescent rates. Alternatively, the Weibull model, used by Herrmann and Konigsberg (2002) in their mortality analysis of Indian Knoll, can be used to integrate a fixed number of disease stages or
insults into the model. Usher (2000) demonstrated the utility of the multi-state Weibull model for capturing different disease states in her analysis of the Danish Tirup cemetery. The Weibull is useful for integrating health indicators as covariates into the model, but does not capture the major features of a human mortality profile as well as the Siler model. Several other models have also been proposed to address mortality and morbidity, but will not be discussed here, as these are outside of scope of this research.

**Pre-industrial population dynamics**

Research examining small-scale populations has the ability to address fundamental questions dealing with the change in fertility and mortality over time and space, the role of ecological factors on population size and growth, and the inter-relationship of size, growth, and health have on a population (Wood *et al.*, 2002). Some researchers have argued that prehistoric mortality patterns are inherently different from all known populations, but with the appropriate information, analytical methods, and interpretations about prehistoric population dynamics are possible (Paine, 2000; Herrmann and Konigsberg, 2002; Chamberlian, 2006).

Based on Malthusian principles, food production and resource acquisition play a critical role in the survival, growth, and reproduction of pre-industrial societies (Gage and O’Connor, 1994; Wood, 1998). With the adoption of cultural ecological models, anthropologists began to examine how human populations have been regulated through cultural practices and belief systems, which led to fertility-based interpretations for maintaining group size. It is now understood that social, historical, and environmental factors all play a role in population dynamics. As Wood (1998: 110) states, a pre-industrial system will move towards a state in which the individual is just good enough to replace himself or herself demographically.
Furthermore, provided with a stable mode of production and controlling for external factors, it is feasible that a population can achieve stability and stationarity in which the crude birth and death rates result in zero population growth. Hypothetically speaking, equilibrium can be achieved in a prehistoric population with a life expectancy at birth of only 20 years, an average of seven births per woman, and an infant/early childhood survivorship approximating 50 percent.

Taking these notions into account and combining the idea that the skeletons within a cemetery are the failures at a particular age (Wood and Milner, 1994), paleodemographic analyses are the study of age-specific survivorship and hazard rates. As can be seen in Figure 3.1, demographers look for three distinct rates associated with mortality curves in order to establish if a trend exists in the data, including the survivorship, hazard, and probability density function curves. Considering only the hazard function, most industrialized populations experience mortality later in life, so an exponential increase is observed in the hazard curve, while the survivorship decreases, and the probability density function approximates zero. The second type is a constant rate of mortality throughout the lifespan, which is observed in the older adolescents and young adults that typically are the healthiest individuals within a population and have minimal age-related risk of death factors. The third type represents mortality that occurs early in life. Similar to most vertebrate species, the risk of death is highest in the first weeks, months, or years. Hewlett (1991) reports that the average infant mortality rates for small-scale societies approximate 20% and can a range from 12 to 28 percent. Mortality declines drastically after infancy with the point of minimum risk between five and 10 years of age (Gage, 2000). The risk of death will remain relatively low until the 30s, where the probability of death begins to increase. The risk of death continues to rise into old age where the hazard rates exceed those
Figure 3.1. The survival ($S(a)$), the hazard ($\mu(a)$), and the probability density function ($f_0(a)$) curves for a typical pre-industrial population (Wood et al., 2002).
observed in infancy (Wood et al., 2002). Overall, a typical pre-industrial population has a U-shaped hazard curve in which infants are at a higher age-specific risk of death, adolescents and young adults have a relatively low risk of death, and older adults have an increasing, high risk of death (Howell, 1976; see Figure 3.1). This attritional model is what would be expected if there were no major influences affecting the demographic parameters. A flatter model with a higher young adult hazard and lower survivorship rate would indicate a catastrophic regime (Paine, 2000).

For example, a skeletal age-at-death distribution resulting from a smallpox epidemic should have an increased hazard rate in the adolescents reflecting a catastrophic pattern. Several non-attributional models have been noted in the recent literature (Chamberlain, 2006). A catastrophic mortality profile has a high risk of death for all age categories, while having an age pattern that mirrors the living population (Keckler, 1997). A catastrophic mortality pattern has an exponential hazard rate (the $\alpha_2$ in a Siler model) for all individual regardless of age. This profile is typical in mass graves associated with epidemics, conflicts, and natural disasters (Gowland and Chamberlian, 2005; Paine and Boldsen, 2002; Margerisan and Knusel, 2002; DeWitte, 2009). Paine and Boldsen (2002) noted that increased population growth, sedentism, and trade caused changes in the patterns of epidemic diseases where there was increased frequency of population disruptions that could be seen in the mortality pattern. Conversely, chronic malnutrition would elevate the young and old more than the middle in the mortality curve across the lifespan. The interrelationship and pattern within the survivorship, hazard, and probability density function permit an analysis of the mortality within and between populations temporally and spatially.
Summary

This research focuses on the utility of one parametric model that incorporates sub-adult and adult mortality, the Siler model, and two adult mortality models, the Gompertz and Gompertz-Makeham models. The Siler model is most applicable for skeletal samples, like the Larson Site, because they require a representative population where under-enumeration of juveniles is a non-issue. The Gompertz and Gompertz-Makeham models are suitable for adult individuals and can better highlight any differential sex-specific mortality in a population over that of the Siler model. While hazard models eliminate many of the issues paleodemographers have with using life tables, issues of over-parameterization are still a problem and must be considered when choosing the appropriate model. Nonetheless, the application of hazard models has improved the capabilities of paleodemographers to model mortality using often incomplete skeletal data.
CHAPTER 4  
Age-at-death Estimation

Age estimation is an essential portion of the development of a biological profile for forensic investigations and for bioarchaeology as it is the foundation for all paleodemographic analyses. Often the skeletal indicators, procedures, and the analytical and statistical methods applied to produce an age estimate are significantly influenced by the research agenda, the statistical understanding, and the philosophical beliefs of the researcher (Algee-Hewitt, 2012). In general, age at death estimates seem fairly straightforward and can be accomplished easily, so it is not uncommon to find a mean age at death, life expectancy, and age-specific mortality rates for a given population. This same assumption has led to the computation of life tables following the modifications outlined in Acsadi and Nemeskeri (1970). For example, the life table produced from the Libben Cemetery can be interpreted in one of two ways; “life was far more difficult for prehistoric North America” or the results are “reductio ad absurdum” which questions the reliability of the life table itself. Howell’s (1982) parameters were so different than Lovejoy and colleagues (1977) that the entire mortality profile was called into question. Several researchers have acknowledged that the means of age-at-death distributions are quite low for several prehistoric samples with some suggesting under-aging of older adults (Weiss 1973; Gage, 1989), others suggest that the use of Bayesian-like approaches are based on reference samples with young distributions (Konigsberg and Frankenberg, 2002), and that the differences in life tables are from the reference samples used to create the age estimates (Bocquet-Appel and Masset, 1982; Buikstra and Konigsberg, 1985). Hence, the problem that often arises in demography analyses of any kind reverts to issues in the age-at-death estimation methods.
The reliability, applicability, and validity of age estimation techniques for paleodemography have been severely critiqued over the past few decades (Bocquet-Appel and Masset, 1982, 1985, 1996; VanGerven and Armelagos, 1983; Buikstra and Konigsberg, 1985; Konigsberg and Frankenberg, 1992, 1994; Bocquet-Appel, 2008; Milner and Boldsen, 2012a, b). Bocquet-Appel and Masset (1982, 1985) argued for the “death of paleodemography” because of inherent issues with age-at-death estimation and the subsequent analyses using these estimations. As Bocquet-Appel and Masset (1982:329) stated, “the information conveyed by the age indicators is so poor” that the estimation of vital rates for past skeletal populations is simply a product of “random fluctuations and errors of method”. They highlighted three major areas of concern in their paper: 1) the target age-at-death distributions are heavily influenced by the distribution of the reference sample used to create the method; 2) age-at-death estimates are inherently biased; and 3) the correlation between skeletal age indicators and chronological age is unacceptably low. However, accurate age-at-death estimations are essential to reconstruct fertility and mortality schedules, morbidity patterns, and the age composition of skeletal populations. Thus, researchers have responded to the concerns by improving on the method and theory in age estimation, which has culminated in the guidelines outlined in the “Rostock Manifesto” (Konigsberg and Frankenberg, 1992, 1994, 2002; Hoppa and Vaupel, 2002) As outlined in the “Rostock Manifesto,” aging methods must incorporate traits that have a better correspondence with age, must utilize Bayesian approaches to create the method used, and must seek to understand the target population’s age distribution (Hoppa and Vaupel, 2002). As several researchers have noted, the ages of skeletal samples are not known (Bocquet-Appel and Masset, 1982, 1985; Konigsberg and Frankenberg, 2002; Van Gerven and Armelagos, 1983;
This results in an inherent error to all age-at-death estimates, which can be alleviated but not resolved by improvements in age-at-death indicators.

Anthropologists typically use a suite of variables from the skeleton, known to change regularly over the course of a lifetime, to infer the chronological age of an individual. A key assumption in using age estimation data to reconstruct the demographic profile of a population is that the biological age, derived from skeletal development and degeneration, is equivalent to the chronological age of the decedent (Kemkes-Grottenthaler, 2002). Variation between the biological and chronological age is known to exist as a result of population differences, secular trends, and susceptibility of the individual to environmental factors. Ideally, the observer wants methods that are both accurate and precise, especially for forensic contexts where only one skeleton is evaluated at a time; while in a paleodemographic context, the goal is to model population dynamics to allow for biological interpretation.

The congruency of the biological and chronological age and the accuracy and precision of methods for age estimation depend on whether estimation is being made on an adult or subadult. Developmental processes are assumed to be under greater genetic control, so are not as affected by environmental influences. Several researchers have found that specific areas of the skeleton are under greater genetic control during development than others (e.g., dentition versus long bone length), and so are not as influenced by environmental changes. Also, populations exhibit differences in rate, timing, and duration of growth. Merchant and Ubelaker (1977) noted a clear difference in growth patterns between the Arikara compared to other Native American and modern American populations. Ubelaker (1978) adapted 20th century American dental eruption standards to account for differences in eruption patterns of the Arikara, and Owsley and
Jantz (1983, 1994) describe how tooth development in infants and children within the Arikara are not consistent with modern standards and suggest a formula to adjust for the difference. On the other hand, adult aging relies on the degenerative process, which is greatly influenced by environmental processes, such as nutrition, lifestyle, disease, or activity. The individual variability of aging in adults results in broader age estimates that are inherently less precise than sub-adult age estimates.

Most age-at-death estimation methods rely on inverse calibration where an appropriate prior (reference population) is required for the computation of quality age estimates. Therefore, whether informal or formal, all age estimation techniques rely on the principles of Bayesian probability (Hoppa and Vaupel, 2002b). Bayesian approaches rely on prior (informed) probabilities to assess the likelihood of age-at-death estimates. Bayesian methods are limited due to the fact that the prior probabilities are influenced by the demographic profile of the reference sample used to develop the method (Bocquet-Appel and Masset, 1982). This is problematic given the majority of reference samples do not resemble a natural mortality distribution. This would not be challenging if age indicators in the skeleton were perfectly correlated with chronological age (i.e., $r$ values close to 1.0). Hypothetically, highly correlated age indicators will maximize the effect of the population dynamics of cemetery populations in a mortality profile, while minimizing the effect of reference sample and “age mimicry” (Mensforth, 1990). However, published correlation coefficients for skeletal indicators and chronological age have never come close to approximating $r = 1.0$ (Kemkes-Grottenthaler, 2002). The reference population’s fitness is one of the biggest obstacles in age estimation. A conservative approach to address the issue of bias is to select a uniform prior when estimating the age distribution of a target sample because it produces an unbiased age structure (Bocquet-Appel, 1986). This classical calibration approach is appropriate when no
suitable prior exists for the target sample, because it assumes an uninformative prior for age at death and produces maximum likelihood estimates for age by regressing the dependent variable on the independent and then solving for age (Konigsberg et al., 1998). It assumes that each skeleton in the target sample has an equal probability of being in all age categories (Hoppa and Vaupel, 2002). A more economical approach would be to utilize statistical methods that incorporate hazard models that allow for the age at death to be calculated from the distribution estimated from hazard analysis and the age of transition (Konigsberg et al., 2008). This method relies heavily on maximum likelihood estimation to produce the age distribution. Maximum likelihood estimates use a reference sample to obtain the target sample age distribution initially, but through multiple iterations, where the subsequent iterations use the distribution of the target sample produced in the first iteration, the effects of the reference sample distribution are minimized (Konigsberg and Frankenberg, 2002). The iterations are maximized when the difference in log-likelihoods between two iterations is negligible. Comparisons of the reference sample, target sample, Bayesian produced curve, and maximum likelihood curve clearly indicate that the maximum likelihood is the best fit for acquiring an age distribution of a target sample (Konigsberg and Frankenberg, 2002). Also maximum likelihood estimation methods can take into consideration the quality of information from an individual skeleton.

**Sub-adult Age Estimation**

Sub-adult aging methods predominantly focus on age dependent variation in dental development, epiphyseal closure, and bone growth to provide an age-at-death. Even though most sub-adult aging techniques provide more precise and accurate ages than adult estimation
methods, sub-adult age estimation methods must account for population specific developmental patterns, because timing and extent of growth are based on the population and sex (Stewart, 1979; Ubelaker, 1978). Also, methods also must account for metabolic stressors affecting growth and catch-up growth often associated with adolescence.

**Dental Development and Eruption**

Teeth are considered to be the most informative and reliable indicator to assess age in juvenile skeletal remains, especially in the very young (Lewis and Garn, 1960; Liversidge, 2008). Teeth have a strong genetic component, so they are not as susceptible to environmental variability; whereas, many of the skeletal markers are affected by nutrition, disease, or maturation variability (Scheuer and Black, 2000; Cardoso, 2007). Smith (1991) found that stages of tooth development had lower coefficients of variation than do stages of skeletal development. Also, dental maturation seems to be independent of both skeletal and sexual maturation (Liversidge, 2008). Furthermore, tests of known age material demonstrated estimated ages diverged less from the actual than from the estimated skeletal age (Saunders *et al.*, 1993).

Anthropologists evaluate dental maturity by 1) assessing tooth crown and root mineralization through the scoring of developmental stages (Morrees *et al.*, 1963a,b; Liversidge, 2008) or by the measurement of the crown versus height (Demirjian *et al.*, 1973) and 2) evaluating the pattern and/or amount of teeth eruption/emergence for age estimations (Schour and Massler, 1941; Ubelaker, 1978). It is important to note that most mineralization standards for teeth are based on cross-sectional or longitudinal studies using radiographs of European children (Smith, 1991), while regression-based methods have utilized documented
archaeological material and are based on measuring the maximum tooth height (Liversidge et al., 1998, 2003).

Out of the several scoring-based approaches available to anthropologists, few meet the “Rostock Manifesto” requirements (Hoppa and Vaupel, 2002). Smith (1991) outlines the mathematical basis for most tooth formation and developmental schemes used in anthropology as well as the pros and cons of each. She focuses heavily on the compatibility and comparability of methods, which according to her are not comparable because “the underlying variables are fundamentally different” (p149). The Moorrees et al. (1963a, b) standards were formed using a probit analysis to locate the mean in the cumulative distribution function, which avoids the age structure bias common to most aging techniques (Smith, 1991). As such, it explicitly provides estimates of age of attainment in the growth stage and provides central tendency and dispersion information. However, Saunders et al. (1993) caution against using the Moorrees et al. (1963b) standards of development for the adult central incisor, because of sampling deficiencies. A recent study by Maber et al. (2006) and Liversidge (2008) evaluated several of the dental maturity methods in use to determine the absolute accuracy of each in regards to the true, chronological age of the child. They found that the scoring based methods performed very well with the overall accuracy being six month to one year.

Several have criticized scoring methods because of the inter-observer bias in the scoring of stages, trait identification, and interpretations of definitions for specific traits, which limits the scoring-based method’s utility (Saunders, 2008). This has led to the development of regression-based approaches. Liversidge et al. (1998) created regression based methods to estimate age
from deciduous and adult teeth, but little research has been published that tests the accuracy level of the regression formulae versus scoring methods.

The comparison of erupted teeth to pictorial charts of eruption patterns also have been applied to archaeological material (Schour and Massler, 1941; Ubelaker, 1978). However, eruption or emergence of the teeth is considered to be less reliable because it is affected by systemic influences, like developmental abnormalities and disease (Smith, 1991). Also, inter-population differences in eruption patterns of teeth have been identified with eruption starting earlier overall or there being a different pattern in the timing of emergence for specific teeth (Jantz and Owsley, 1994). Ubelaker (1978) adapted the developmental stages for the first 15 years of life chart, created by Schour and Massler (1941), for Native American materials to account for this. Merchant and Ubelaker (1977) found that Arikara Indian material from the Mobridge (39WW1) archaeological site displayed earlier than expected eruption patterns when compared to ages obtained through Moorrees et al. (1963a,b). However, this test of Schour and Massler (1941) used materials of an unknown age. Nevertheless, Ubelaker’s (1978) eruption chart is the recommended source for most of forensic anthropology and was cited as such in the Workshop for European Anthropologists (1980). Another possible source of error in using tooth eruption for age estimation is in the definition of eruption. Most clinical-based standards consider eruption when the tooth has perforated the gingiva; whereas in archaeological contexts eruption is often associated with the tooth projecting beyond the bone (Smith, 1991).

More recently, Shackelford et al. (2012) outlined a multifactorial method for dental development based on the Moorrees et al. (1963a,b) method. Since the Moorrees et al. (1963a,b) data follow a cumulative probit distribution, Bayesian based methods can be applied in which the
transition of moving from one score to the next can be determined for individual or a suite of teeth. A specific point estimate and probability density function for the age can be determined using combined data from both primary and secondary teeth.

**Skeletal Development**

The appearance of ossification centers are the least informative in bioarchaeological analyses, because separate ossification centers cannot be clearly associated with elements when excavated. However, the overall size and morphological changes of ossification centers are a primary means to assess age from the mid-fetal to the late adolescent time period, especially in the absence of teeth. Surveys of archaeological and forensic materials by Ubelaker (1978, 1989 a,b) have provided much of the information regarding fusion times found in Buikstra and Ubelaker (1994). These data augmented by McKern and Stewart’s (1957) survey of Korean War fatalities provide an extensive overview of skeletal maturation timing. The caveat with using McKern and Stewart (1957) as a standard in the archaeological context is the narrow population scope, so other references should be used in conjunction with or in lieu of this reference (Ubelaker, 1978; Stewart, 1979; Scheuer and Black, 2000). The timing of epiphyseal fusion, even though it is well documented, is quite variable by individual, sex, and population (Cameron, 2002; Crowder and Austin, 2005; Saunders, 2008). Studies have consistently demonstrated that epiphyseal fusion occurs earlier in females than males (Scheuer and Black, 2000; Krogman and Iscan, 1986). The value of epiphyseal fusion and long bone length increases when analyzing older children and adolescent material, but sex of the individual should be considered in these cases (McKern and Stewart, 1957; Stewart, 1979; Ubelaker 1989, Scheuer and Black, 2000).
The postnatal change in long bone length has been well documented by Maresh (1943, 1955, 1970) for living children of European descent. He has established reference tables from birth to the cessation of growth in length of most major long bones, which can be found in *Developmental Juvenile Osteology* (Scheuer and Black, 2000). The Maresh standards have been widely applied to assess the predicted length in archaeological sub-adult remains. However, there is no way to verify the age estimates in archaeological remains, so studies have correlated long bone length with dental development (Johnston, 1962; Merchant and Ubelaker, 1977). Jantz and Owsley’s (1994) suggest that the deciduous teeth in Arikara children did not develop in relation to one another in the same way as those of children used in establishing White standards. For example, the stages for the second deciduous molar are attained earlier in Arikara children. Owsley and Jantz (1984) examined the perinatal profile using long bone lengths compared to dental development and found that a large number of infants may represent premature births or were smaller skeletally for their age. Konigsberg et al. (1997) used the femoral length on age with maximum likelihood method to re-estimate the age-at-death distribution and found that more of the skeletons were term. Most studies have relied on teeth as the basis for examining growth, because skeletal age has served more as a marker for alterations and defects in growth than to estimate age for archaeological material (Saunders, 2008).

A major concern in the assessment of age-at-death in juvenile archaeological material is the preservation of reliable indicators. Eruption and development of teeth, the presence and appearance of ossification centers, epiphyseal development, epiphyseal fusion, and bone length as a means to assess age-at-death have all been applied to archaeological materials (Scheuer and Black, 2000; Krogman and Iscan, 1986; Ubelaker, 1978; Ubelaker, 1989). Most studies have
utilized teeth, but have substituted long bone length derived ages when teeth are unavailable. Caution is suggested when using skeletal development when dentition is available as there is considerable variation in maturation rates on the inter-personal level (Cameron, 2002). Thus the challenge that arises with archaeological material is that a large disparity often exists between the ages derived from teeth compared to those that are derived from long bone length or skeletal development. The disparity between dental and skeletal maturation is of importance in studying the Arikara in the Missouri River Basin of South Dakota. As early as Johnston (1962), a difference was noted between expected skeletal lengths compared to ages derived through dentition in the juveniles at Indian Knoll, an Archiac Native American population. Owsley and colleagues (1983, 1994) evaluated 18\textsuperscript{th} and 19\textsuperscript{th} century Arikara, who demonstrated a low rate of diaphyseal increase with age compared to other archaeological material. They suggest that epidemic disease, depopulation, and inter-tribal conflict caused the stress. Merchant and Ubelaker (1977) examined proto-historic Arikara from Mobridge, South Dakota and found precocious dental eruption when compared to European-based standards. Owsley and Jantz (1994) noted a difference in dental formation rates compared to long bone lengths in Arikara infants and proposed a correction factor that accounted for the significantly shorter long bone lengths for perinatal remains than expected based on their dental development.

**Adult Age Estimation**

While sub-adult age estimation methods focus on the correlation between biological and chronological age associated with development, methods employed in bioarchaeological analyses of mature remains rely on the predictability of degenerative processes within the skeleton. A plethora of adult age-at-death estimation methods have been devised by the
anthropological community ranging from single trait methods to complex multifactorial summary age methods (Kemkes-Grottenthaler, 2002). Many anthropologists have relied on “traditional,” macromorphoscopic-based, age-at-death estimation methods found in the Standards of Data Collection (Buikstra and Ubelaker, 1994), which have become the foundation for many population studies over the last several years. Single trait methods have ranged from observing gross morphological observation using the pubic symphysis (Todd, 1920, 1921a/b/c; McKern and Stewart, 1957; Suchey et al., 1986), auricular surface (Lovejoy et al., 1985a; Buckberry and Chamberlain, 2002; Igarashi et al. 2005), acetabulum (Rissech et al., 2006; Calce 2012), sternal rib ends (Iscan et al., 1984, 1985; Yoder et al. 2001; DiGangi et al., 2009), and cranial sutures (Todd and Lyon, 1924, 1925; Singer, 1953; Meindl and Lovejoy, 1985; Mann et al., 1991; Nawrocki, 1998). Several multifactorial methods have been developed (Acsadi and Nemeskeri, 1970; Workshop of European Anthropologists, 1980; Lovejoy et al., 1985b; Boldsen et al., 2002; Weise et al., 2008). Other methods have focused on microscopic and histological techniques to evaluate cortical bone remodeling rates (Kerley, 1965; Kerley and Ubelaker, 1978; Stout and Paine, 1992), dental histology, and root translucency (Maples, 1989; Lamendin et al., 1992; Prince and Ubelaker, 2002). Reviews of age estimation methods available can be found in Kemkes-Grottenthaler (2002), Latham and Finnegan (2010), and Garvin et al. (2012). The over-arching theme to all aging is the predictability of observable morphological change over time.

**Traditional Trait-based Methods**

The pubic symphysis is one of the most reliable single-trait age-at-death indicators available (Meindl and Lovejoy, 1985) and performs the best in comparative studies (Milner and Boldsen, 2012 a,b). Todd (1920, 1921) was one of the first to establish a phase system to
describe the age-related changes in the pubic symphysis. His ten phases have increasingly wider age ranges to account for the variability in age-related morphological change with an open-ended terminal phase X that captures individuals 50 years or above. Researchers have continually revised this method by developing new ways to quantify changes and produce an age estimate (McKern and Stewart, 1957; Gilbert and McKern, 1973; Katz and Suchey, 1986).

McKern and Stewart (1957) developed a component scoring system that used Todd’s (1920) descriptions for an all-male sample of Korean War dead. A female equivalent was developed by Gilbert and McKern (1973). The McKern and Stewart (1957) method computes a composite score (0-15) from three areas of the pubis symphysis: the dorsal plateau, ventral rampart, and rim, which is then compared to a chart with known ages. They believed that this was less biased and restrictive than the Todd (1920) method and addressed the criticisms of Brooks (1955), which suggested that Todd (1920) did not account for the variability within a specific age interval and thus over-aged individuals. The component system’s biggest drawback is that it requires a complete, well-preserved surface so that all features can be scored.

Katz and Suchey (1986) re-evaluated the pubic symphysis using a forensic population with known ages ranging from 14-92 years derived from the Los Angeles Medical Examiner’s office. Their study was one of the first to capture older individuals that had been underrepresented in reference sample age distributions. They believed that the features highlighted in McKern and Stewart’s method are not independent, so an approach that accounts for the entire surface is better. Katz and Suchey (1986) modified Todd (1920) into 6 phases with 95% age intervals associated with each phase. Brooks and Suchey (1990) further refined Todd’s method for females. Katz and Suchey (1986) and Brooks and Suchey (1990), better known as the Suchey-
Brook’s method, is the most common method applied in modern forensic case work in the United States (Garvin and Passalacqua, 2011). Refinements to the Suchey-Brook’s system have been published that acknowledge a seventh phase to capture more advanced ages, but these methods remain untested (Berg, 2008; Hartnett, 2010). One of the biggest criticisms of the Suchey-Brook’s method is that it has very wide age ranges, which may or may not be useful in the forensic context. More important to this research is the fact that the Suchey-Brook’s method is statistically limiting, because it cannot be used to construct demographic life tables with more than six parameters (Boldsen et al., 2002).

The auricular surface has been widely used in paleodemographic analyses since its inception by Lovejoy et al. (1985a) who noted the preservation of this surface over other skeletal elements. Lovejoy et al. (1985a) outlined eight phases associated with the changing morphology with age of the auricular surface. However, the Lovejoy et al (1985a) method has an open-ended terminal age range of 60+ years like that of the Todd method. Murray and Murray (1991) criticize the Lovejoy et al. (1985a) method from a forensic standpoint because the degenerative changes are too variable. They call into question the precise age ranges published by Lovejoy et al. (1985) and suggest that the error is too large. However, Lovejoy et al.’s method (1985a) is not as influenced by inter-population affects or secular change as other techniques (Osborne et al., 2004). Osborne et al. (2004) calculated new mean ages and a 95% prediction interval for a modified six phase system from the original Lovejoy et al. (1985a) eight phase system, which is more appropriate in the forensic context.

Like the pubis symphysis, anthropologists found the variability within the surface morphology too complex to be captured in one phase (Buckberry and Chamberlian, 2002).
component system utilizes individual scores for transverse organization, surface texture, microporosity, macroporosity, and apical changes to compute a total score that is compared to known ages (Buckberry and Chamberlian, 2002) much like that of McKern and Stewart (1957). As with other component systems, all features must be present to properly use the system. Igarashi et al. (2005) devised a system using 13 binary traits from the auricular surface, which did not have to be complete; however, the composite scores had little improvement in reliability over previous systems.

The ossification of the costal cartilages has been acknowledged in the literature, most notably by McCormick (1980), but Iscan et al. (1984a,b) fully developed the phase-based age-at-death estimation method for sternal rib ends commonly used in biological analyses. This method utilizes the pit depth, pit shape, and rim wall morphological changes associated with age to assign the sternal end of the fourth rib to one of eight phases. The eighth phase is an open-ended terminal phase like the other single-trait phase-based approaches available. Criticism of this method draws from the variability within each phase, the specificity of sex and population, and the need to identify the fourth rib. Others have suggested the use of the first rib, because it is easy to identify and is usually better preserved (DiGangi et al., 2009).

Cranial sutures have had a long tradition of study in anthropology. As early as Todd and Lyon (1924, 1925a,b,c), the age ranges produced from observations of the cranial sutures were criticized as being too broad and not very reliable. This did not discourage use of cranial structure as it is the main method utilized when a cranium is the only material available to be analyzed. Meindl and Lovejoy (1985) established a four point scoring system from 0 to 3 to represent the degree of closure at ten specific ectocranial (1 cm) sites across the cranium in
which a composite score could be compared to a table of known ages. Meindl and Lovejoy (1985) divided the sites into vault and “lateral-anterior” systems. It is recommended to use the latter over the former as it is not as affected by an individual’s biology. A similar method was devised for the maxillary and palatal sutures by Mann et al. (1991). The cranial suture scoring system was further refined by Nawrocki (1998). He expanded the sutures scored to include the palate and endocranial sutures, and he calculated group specific regression equations integrating specific sutures. Nawrocki’s system was tested by Zambrano (2005) using modern material and found that the all-group equation preformed the best, but the age intervals were quite wide. He also reaffirmed the sex specificity of cranial suture closure. A similar argument was made by Milner and Boldsen (2012 a,b) where the addition of cranial sutures caused little change in their maximum likelihood estimates for age-at-death because the age ranges were so wide. Even though it does not provide much more information beyond indicating an adult individual is present, it is still a good line of evidence if only the cranium is present.

Phase approaches have long been used in anthropology and are typically favored over component scoring methods for individual traits. The use of phases requires the visual comparison of a specimen to a reference exemplar and textual descriptions of that exemplar. It relies on an age assignment based on the relationship between a phase and known reference samples in the literature. However, there are several underlying problems with phase based approaches. The first and foremost problem is that needed morphological features for age estimation are often absent, usually from taphonomic processes. Additionally, inter- and intra-observer error can be problematic because definitions may be difficult to understand, unclear, or are not well defined. Often the age intervals are broad with the terminal phase being open-ended.
or the phases overlap. Alternatively, there is a high amount of variation within a single phase. Often the statistical probabilities or significance of a phase are not part of the research establishing an age-criterion. Also, the estimates are often biased, so that individual ages are under or over-estimated as the tendency is towards the mean (Hoppa and Vaupel, 2002). Furthermore, traditional aging methods rely on inverse calibration techniques to determine an age where the distribution of indicators are plotted against known ages from a reference sample to estimate the distribution in an unknown, target sample. However, these methods produce biased estimates because they assume that the reference sample and target are dependent on each other (Konigsberg and Frankenberg, 1992, 2002). Often the target sample age distribution mimics that of the reference sample (Mensforth, 1990). Since it is impossible for the reference and target samples to be independent, statistical tools need to be used to limit the bias and avoid total “age mimicry.” A classical calibration technique that regresses the indicator on age and then solves for the age is more appropriate from a statistical perspective.

**Multifactorial Methods**

A prevailing argument against single trait methods is the complexity of the aging process within a single individual (Milner and Boldsen, 2012). It is not uncommon to have bilateral asymmetry or differences between two different indicators (Kemkes-Grottenthaler, 2002). Single trait methods are applicable if one trait is available for age estimation, but the aging process is variable across the entire skeleton making it too complex to rely on a single age indicator. Even Todd (1920) noted that no single part of the skeleton is infallible and that an accurate age is estimated only after the examination of the entire skeleton. Hence, most individuals utilize a suite of traits combined with their experience to produce an age range for a single skeleton. The
use of multiple indicators does not necessarily remove the issue of reference sample bias of the individual traits (Milner et al., 2008). Baccino et al. (1999) compared seven different aging methods using four approaches to calculate an age-at-death estimate. They evaluated single traits, a mathematical average of traits, a two-step approach, and a global approach and found that comprehensive methods performed better than single trait methods. A prevailing consensus, in line with the “Rostock Manifesto,” is that Multifactorial aging should be applied in estimating ages from morphological observations, because this provides a more holistic understanding of the ageing process. However, few solutions that statistically conform to the “Rostock Manifesto” have been consistently applied in the literature. The biggest problem in using multiple lines of evidence is to find the most statistically appropriate method for combining the information from multiple traits.

*Regression Approach*

Gustafson (1950) was one of the first to integrate multiple indicators using a regression model that utilized six variables from teeth. The sum of the point values for each variable was compared to a standard curve to estimate age. Other researchers have been unable to replicate his results largely from the issues with error and inappropriate application of regression for the sample size given (Kemkes-Grottenthaler, 2002). A complex method formulated by Ascadi and Nemeskeri (1970) and later adopted by the Workshop of European Anthropologists (1980), averaged four indicators (cranial sutures, pubic symphysis, humerus, and femur). Each indicator was incorporated into a regression formula with equal weight and then compared to known age tables. This method has been heavily criticized because of the equal weighting of traits without clear justification for doing so. Additionally the equal weighting causes both an under aging of
older adults and an over aging of the young, which has led to the argument that regression based methods cause an attraction towards the mean (Lovejoy et al., 1985b; Meindl et al., 1985; Kemkes-Grottenthaler, 2002). The main issue that arises with the integration of single traits into a regression model is that the statistical methods often applied require the assumption of independence of traits which causes a collinearity problem. The more recent methods rely on regression of the independently scored “traditional” features to create a new estimate (Aykroyd et al., 1999; Martrile et al., 2007; Uhl, 2008), which could be compounding error if done incorrectly. While most agree that researchers should use everything they have, most will still weight age criteria on personal preference and familiarity (Garvin and Passalacqua, 2012) rather than apply a statistical method to produce an age estimate.

Multifactorial Summary Age Method

Lovejoy et al. (1985b) suggested the Multifactorial summary age method, which utilizes the pubic symphysis, auricular surface, cranial suture closure, dental wear and radiographs of the proximal femur. The authors call for the seriation of skeletons for each age indicator in a sample to maximize information from biological age and minimize observer error across observations; however, seriation creates a problem of lack of independence and can hamper the decision making process as to the transition from one age to another (Konigsberg and Frankenberger, 2002). Seriation of traits was the first step in the Multifactorial method, which integrated the five aforementioned indicators to create a population matrix. A principal component analysis was applied to the population matrix and the correlation of each indicator with the first principal component became the indicator’s weight (Lovejoy et al., 1985b). The age was the weighted
average of all chosen indicators. Bedford (1993) conducted a blind test of this multi-factorial method, and found that the “summary” ages strongly correlated with each other.

**Bayesian Multifactorial Method**

Uhl and colleagues (2011) presented a Bayesian approach to Multifactorial aging that allows researchers to incorporate multiple skeletal indicators of age-at-death in a statistically sound way. This Multifactorial approach is a statistical combination of several age estimates using data for the pubic symphysis, the auricular surface, and the sternal rib end collected following the methods of Suchey and Brooks (1990), Lovejoy *et al.* (1985a), and Iscan *et al.* (1984a, b, 1985). After testing if the original scoring systems followed a Transition model, Uhl *et al.* (2011) found that all but the auricular surface followed a cumulative log-probit model so the phases for this surface were condensed to five phases. Testing of the model showed that it was able to capture 95% of the individual ages within the 95% highest posterior density regions; however the ranges were quite wide in some instances, especially for the very old (Uhl, 2013). This method has the capability to handle missing data, bilateral asymmetry, and does not require additional data collection for a new aging method, which Transition Analysis requires. This method can be applied to individual cases through the use of reference tables, the scores from the traditional age estimation methods, and computation as outlined in Uhl (2013).

**Transition Analysis**

Konigsberg and Frankenberg (2002) demonstrated that maximum likelihood estimation methods using multiple indicators outperform the Multifactorial approaches because they produce more representative target age distributions. One of the key benefits of a maximum likelihood approach is the ability to integrate multiple age indicators, without introducing
unnecessary bias seen in Lovejoy et al. (1985b), to produce an age estimate (Konigsberg and Frankenberg, 2002). Transition Analysis estimates age of transition between adjacent stages of a phase or trait (Boldsen et al., 2002). Konigsberg and colleagues demonstrated that it is possible to compute the probability density function for a mean age at transition for any single trait that can be reliably seriated and follows a consistent aging scheme (DiGangi et al., 2009, Langley-Shirley and Jantz, 2010). The basis of Transition Analysis is that a probability of being in a morphological state is calculated from a known age sample. These parameters are converted via maximum likelihood estimation to a mean and standard deviation for a distribution of the age (Boldsen et al., 2002). Several individuals have shown the utility of Transition Analysis in paleodemographic research (Usher, 2000; DeWitte, 2009; Wilson, 2010).

Transition analysis, as it is presented here is referring to the system and computer program established by the Anthropological Database Odense University (ADBOU), University of Southern Denmark, which utilizes the scoring of several discrete traits on an ordinal scale to calculate an age estimate and the posterior probability density using Bayesian inference and maximum likelihood estimation for each trait as well as for the combination of traits (Boldsen et al., 2002). Transition Analysis, as described by Boldsen et al. (2002), addresses several of the concerns relating to age estimation: uncertainty of the estimate, age mimicry of the reference sample, the integration of multiple traits, capturing the morphological variability within a given trait, and open-ended age intervals. It conforms to the “Rostock Manifesto” in that it calculates, using Bayesian inference and maximum likelihood estimations, the individual age of a skeleton, but it does not calculate the age distribution of the target sample directly from the skeletal traits, that the “Rostock Manifesto” requires.
Transition Analysis offers several benefits over traditional phase and component scoring systems. Transition Analysis is equivalent to a component scoring system, which alleviates inter-observer error issues by utilizing binary or ordinal traits. It can be applied to any indicator that undergoes regular, progressive changes throughout life, so it substantially increases the number of scoring areas which increases the quality of an individual estimate. It can handle missing data, which other component systems cannot. Most importantly, Transition Analysis as applied in ADBOU, can account for the uncertainty of an age estimate. The measure of uncertainty is a growing concern in the forensic community, as outlined by the National Academy of Science’s Report (2009), which suggests practitioners must account for the reliability and validity of their measures. The certainty of an age cannot be determined in many current methods (Milner and Boldsen, 2012b). It is difficult to determine central tendency and dispersion of a reference sample, because it is often left unpublished by the developer of a method. The application of likelihood curves allows for a true measure of uncertainty associated with a trait or suite of traits, which is provided via the 95% confidence intervals. Boldsen et al. (2002) and Buikstra et al. (2006) demonstrate Transition Analysis can provide information about ages of the old in much different samples, so researchers are not forced to record open-ended intervals (e.g. 50+). In fact, Milner (2010) and Milner and Boldsen (2012a, b) have shown that the confidence intervals for older individuals are narrower than the middle-aged individuals when using an informative prior. Also, the fixed age intervals associated with phase systems assume a universal uniformity to an age distribution within a given interval, which is not the case in Transition Analysis.
Bethard (2005), Uhl (2008), and Milner and Boldsen (2012 a, b) found that the Transition Analysis method, using the computer program ADBOU, was only moderately effective in estimating age-at-death. The main criticisms of the ADBOU program is that the built-in priors are not relevant to all situations, the program does not allow for the flexibility of integrating other aging criteria, and that the complexity of the scoring system required to use the program is difficult for those accustomed to the traditional phase approaches (Uhl 2013). There is still the possibility of attraction towards the mean if an improper prior is used for the maximum likelihood estimation, because this prior is a reference sample from which individual estimates are drawn. Additionally, without prior experience in the scoring system, inter-observer and intra-observer error become problematic, but this can be alleviated with a little training. Others have found it useful to incorporate multiple skeletal indicators in a relatively unbiased fashion (Wilson and Algee-Hewitt, 2009; Shirley et al., 2010; Wilson 2010). These positive results using Transition Analysis, suggest that the inconsistencies observed in the quality of multi-trait estimates may be a result of the individual research design, methodological choices, and statistical assumptions and not the underlying theoretical foundation that supports the combined approach.

**Summary**

Going back to an earlier statement by Dr. Maples (1989:323) “Age determination is ultimately an art, not a precise science…the final best estimate results from a subjective weighting of all of the techniques that were employed.”. While some indicate that all of our scientific endeavors really do not provide much better results than our subjective “art” does for age estimation
(Milner and Boldsen, 2012); I agree with Kongsberg and Frankenberg (2002:253), there is “no apparent reason why we should not strive to make it a science.”. The Bocquet-Appel and Masset (1982) requirement of a 0.9 correlation coefficient for each age indicator is unrealistic because of the variability in the aging process within a skeleton. However the use of multiple age indicators in methods like Transition Analysis allow for more accurate age estimates based on Bayes’ theorem and maximum likelihood estimation (MLE), which do not have the reference sample age distribution bias. Even though the method does not recover the parameters of the age-at-death distribution like other methods (e.g., Konigsberg and Herrmann, 2002; Love and Müller, 2002), it does not have the issues of subjectivity of phase age-at-death methods, can handle multiple age indicators, and can act as a first step in creating a mortality profile.
CHAPTER 5
Materials and Methods

Materials
A sample from the Larson Site (39WW2) located in south-central South Dakota was utilized in this analysis. Excavation of the cemetery associated with the Larson Village started in 1966 and continued through 1968. Heavy mechanical equipment, trenching, and traditional hand excavation methods were utilized to recover all skeletal material within the cemetery area during the salvage operations, as this site is now under the Oahe reservoir. In total 706 individuals were recovered from the village and adjacent cemetery. Although no site report has been published, the Larson Site has been utilized in several research projects. A relatively short occupation time, 1750 to 1785, for the village has been suggested (Jantz, 1970; Lehmer, 1970; Owsley, 1975; Owsley and Bass, 1979), Jantz and Owsley (1985) suggested a 1679-1733 protohistoric occupation date, and more recently a 1700-1725 date was suggested (Billeck and Dussubieux, 2006). Nevertheless, cultural assignment is post-contact Coalescent tradition (Lehmer, 1971), Le Beau phase. Furthermore, European manufactured goods were recovered in association with many of the cemetery burials indicating a post-contact village (Jantz, 1972).

The Larson Site consists of an earthlodge village and cemetery located on the east bank of the Missouri River just south of Mobridge, South Dakota. The village was located on a high terrace overlooking the valley basin with the cemetery located 100-300 yards northeast of the village (Owsley et al., 1977; Owsley and Bass, 1979). The settlement was fortified by a defensive ditch (Bower, 1966). The locality of the cemetery, in proximity to the village, is
consistent with Arikara ethnohistoric data (Lehmer, 1970). Figure 5.1 provides a map of the excavated areas associated with the Larson Site from the 1966, 1967, and 1968 field seasons.

Burials were excavated in the village area and from the cemetery which was east of the village. Initial investigations by Bowers (1966) indicated human remains inside lodges and the village area (Owsley et al., 1977). The village area is not included in this analysis due to the village site formation processes. The condition of the remains, location within the lodges, and artifacts found in association with these remains imply a hostile etiology (Owsley et al., 1977). Also, the skeletons displayed evidence of scalping, fractures, mutilation, and dental avulsion irrespectively of age or sex (Owsley et al., 1977). Subsequent salvage based excavations by a team from the University of Kansas under the direction of Dr. William M. Bass, 1966-1968, led to the recovery approximately 620 individuals from approximately 700 burials in the cemetery area (Oswley and Bass, 1979). The field workers had to contend with rising water levels throughout the excavation period, some skeletons being washed away, especially those in 1968, and many excavations occurring in thick mud and underwater (n.d. field notes). The excavation conditions did effect the preservation of skeletal material with many of the skeletons in the F301 feature being incomplete and exhibiting extensive cortical exfoliation that often is associated with wet burial conditions. However, it is estimated that approximately 90% of the cemetery was excavated and recovered (Bass and Rucker, 1976).

In the 1970s, Dr. Bass transferred the skeletal remains from the University of Kansas to the University of Tennessee. Preliminary analyses by Bass and Rucker (1976) suggest the Larson cemetery was representative of the expected population; because of an equal number of
Figure 5.1 Plan map of the excavated burials from the Larson Site (39WW2). Adapted from Owsley (1975, p. 14).
males and females were found. Additionally, Lehmer (1970) indicates that the Arikara did not have differential treatment of remains. However, Hurt (1969) suggests that at certain months the village would have only been occupied by the indigent (sick, elderly, injured) and children, which may have caused a bias in the cemetery composition.

All materials that could be associated with a specific burial number and were available to this author were examined, (N=620). The original number of skeletons associated with the cemetery, based on field records, suggests a total of 643 individuals. During analysis it was discovered that a few of the juvenile individuals actually represented multiple individuals, so they were distinguished as such during analysis. Also, several adult skeletons were not available to this author at the time of analysis, so they were eliminated from subsequent analyses. The number of skeletons available, the good ethnographic, historical, and archaeological data, and the wealth of research on the biological affiliation of the individuals of the Larson Site make it an ideal candidate to test the applicability of paleodemographic model construction and the age-at-death estimations necessary for these models.

A total of five datasets were developed from the age and sex data as shown in Table 5.1. All datasets included only the individuals that could be given a specific age-at-death estimate with a 95% confidence interval and only those adults that could be confidently ascribed to a sex. The datasets included two datasets that included adult ages derived from transition analysis, two datasets that included adult ages derived from the multifactorial approach, two datasets that included juvenile long-bone length-based age-at-death estimates, two datasets that included juvenile dental mineralization-based age-at-death estimates, and one dataset based on Owsley’s (1975) original age-at-death data. Thus the five datasets are as follows 1) transition
analysis/dental, 2) transition analysis/skeletal, 3) multifactorial/dental, 4) multifactorial/skeletal, and 5) Owsley. The size of the five datasets depended on the availability of the skeletal materials and the presence of the relevant age indicators within the individual skeletons. Several adult individuals could not be re-analyzed since they were unavailable to this researcher during data collection.

Table 5.1. Sample size and composition of the five datasets used to examine the mortality of the Larson Village cemetery.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owsley</td>
<td>584</td>
</tr>
<tr>
<td>Transition/Skeletal</td>
<td>611</td>
</tr>
<tr>
<td>Transition/Dental</td>
<td>472</td>
</tr>
<tr>
<td>Multifactorial/Skeletal</td>
<td>581</td>
</tr>
<tr>
<td>Multifactorial/Dental</td>
<td>444</td>
</tr>
</tbody>
</table>
Methods

This research is the first stage of a larger project to evaluate the “well-being” of the Arikara throughout the Missouri River Valley. The ultimate goal is to apply an epidemiological model that integrates both the demographic and pathological data, but this cannot be accomplished without understanding the population dynamics within each skeletal population. The scope of this work will be limited to understanding 1) how age-at-death estimation methods impact demographic reconstruction and 2) what information can be gleaned about the Arikara from the demography of the Larson Site (39WW2) cemetery skeletal sample. Examining the differences between age estimation methods permits a better understanding of sample construction and any associated biases. Each age-at-death distribution will be used to evaluate the fit of demographic models in order to better understand population dynamics associated with post-contact Arikara.

Age-at-death Estimation

Accurate age-at-death estimates are vital to bioarchaeology analyses, as they serve as the basis for population-based analyses. Age-at-death estimates for all skeletons were calculated using multiple lines of evidence. The following sections outline the methods used to estimate age-at-death in juveniles and age-at-death and sex for adults. All age-at-death estimates accounted for gestation, so they were systematically adjusted for the nine month gestation period or 0.75 years for consistency purposes. Since skeletal development is initiated in utero and most of the primary dentition is well-developed prior to birth it is necessary to have age ranges that incorporate fetal ages.
Sub-adult age-at-death Estimation

Sub-adult age-at-death estimates utilized previously established methods for dental development (Moorrees et al., 1963 a,b; Shackelford et al., 2012; Liversidge et al., 1998), bone length measurements(Maresh, 1955; Fazekas and Kosa, 1978); and epiphyseal development, union, and fusion (Buikstra and Ubelaker, 1994; Scheuer and Black, 2000). A few standards are available, relevant to Native Americans and more specifically the Arikara (Jantz and Owsley, 1994; Ubelaker, 1987, 1989), but were not implemented in this analysis as they do not follow the guidelines suggested by the “Rostock Manifesto” (Hoppa and Vaupel, 2002) and do not completely account for the biases associated with precocious dental eruption and development compared to skeletal development. Furthermore, these works served as the justification for keeping skeletal development and dental development based age-at-death estimates as separate data sets.

Cranial and long bone lengths (maximum diaphyseal length) for fetal and infant remains were taken with a digital sliding caliper. All available left side elements were measured. The right side was substituted when the left was unavailable. Age was acquired through a comparison of the cranial and post-cranial metrics from reference tables created by Fazekas and Kosa (1978), as presented in Scheuer and Black (2000), for fetal remains. Long bone lengths for infant through adolescent remains were taken with a digital sliding caliper or osteometric board, as appropriate, and compared to growth charts presented by Maresh (1955), which are based on healthy American children. No applicable growth charts were available for Native Americans.

Dental development scores were assigned by visual assessment of the dental mineralization pattern following Moorrees et al. (1963a, b) or by regression analysis following...
Liversidge et al. (1998). Moorrees et al.’s (1963a, b) study was based on a large, longitudinal sample from dental radiographs of children at the Fels Research Institute in Ohio and utilize a cumulative probit regression model on a log scale to estimate developmental levels (Smith, 1991). The Moorrees et al. (1963a, b) charts were previously utilized to study the Larson Site (Owsley, 1975; Owsley et al., 1977; Owsley and Bass, 1979), but these analyses did not capture the scores for all teeth simultaneously; rather single tooth scores and associated ranges were given preference to assign an age range. Preference was given to premolar and molar scores to assess age (Owsley and Jantz, 1983, 1984). The age estimates for juveniles with teeth that could be scored following Moorrees et al. (1963a,b) were calculated following the maximum likelihood estimation (MLE) method outlined by Shackelford et al. (2012) using the R, version 2.15.1, statistical platform (http://www.r-project.org). Shackelford et al.’s (2012) method permitted the integration of all available scored teeth into a MLE equation using R. Very young infants could not be assessed using the method outlined in Shackelford et al. (2012), as Moorrees et al.’s (1963a, b) data did not include fetal or newborn teeth. When only the deciduous dentition, in the early stages of development, was available, regression formulae developed using the Spitalfields archaeological collection of known age-at-death individuals were utilized (Liversidge et al., 1998). This method used the maximum length (cusp-tip or mid-incisal edge to developing edge of crown or root) of the developing tooth to estimate the age.

Long bone length-based methods and dental development-based methods served as the basis for all sub-adult ages obtained in this research. No substitutions were undertaken and dental and skeletal age estimates were analyzed separately and compared to the age estimates provided in the curation records. Growth studies of Arikara skeletal materials have suggested
differences in growth patterns of teeth and long bones compared to modern Americans and other archaeological materials (Merchant and Ubelaker, 1977). Owsley and Jantz (1983, 1984) identified systematic and patterned differences in tooth formation timing in the Larson Cemetery sample for infants and young children. They found a significant difference between the age estimates obtained by teeth and those obtained through skeletal development and suggest a correction factor for age estimates. Konigsberg and Holman (1999) suggest age-at-death methods for immature remains are not free from the reference sample age-structure bias seen in methods for aging adult skeletons, so the correction factor suggested by Owsley and Jantz (1994) was not applied to the sub-adult age estimate. Furthermore, the correction factor was only applicable to the very young. Others have suggested that age-at-death estimation method biases are minimal compared to the adults, so they would not drastically affect paleodemographic analyses (Milner et al., 2008). Milner et al. (2008) go on to state that the margin of error and variation within individual age estimates will not drastically affect analyses of juvenile mortality, survivorship, and fertility (Milner et al., 2008). Since previous research has suggested a significant difference between Native American, specifically the Arikara, skeletal and dental development, this research evaluates the influence of the age-at-death method on modeling the juvenile mortality parameters. Thus, the data from the curation records, from skeletal development and from dental development, were treated as separate data sets.

**Adult Sex and Age-at-Death Estimation**

Previous research has indicated difference between male and female mean ages-at-death in the Larson Cemetery (Owsley and Bass, 1979), so sex was estimated for all adult skeletons available to the author. This allowed for the assessment of sex-specific mortality. Sex estimates followed the standard scoring approaches presented in Buikstra and Ubelaker (1994) for
innominate and cranial morphology. When available the attributes associated with the pubis (Phenice, 1969) were given preference over other methods as these traits have been found to be more accurate. The greater sciatic notch scores were evaluated using Walker (2005). Cranial morphology was assessed when these were the only traits available for analysis and followed the methods outlined in Walker (2008). Care was taken to assess sex using just cranial elements when the individuals appeared to be older, since Walker (2008) has shown that more robust, older females have been attributed to males because sexual dimorphism is reduced with advancing age (Meindl et al., 1985; Walker, 1995; Meindl and Russell, 1998).

All adult individuals were scored following the “traditional” age estimation methods outlined in Buikstra and Ubelaker (1994), the Transition Analysis scoring guidebook (Milner and Boldsen, 2008), and the Calibrated Expert Inference approach (pers. comm. Dr. George Milner). These scores were then used to estimate the age at death through the application of Bayesian Multifactorial Analysis (Uhl et al., 2011; Uhl, 2012) that uses scores obtained from the Suchey-Brooks method (Brooks and Suchey, 1990), Iscan et al. (1984a,b; 1985), and Lovejoy et al. (1985a), Transition Analysis (Boldsen et al., 2002), and the Calibrated Expert Inference approach (Weise et al., 2008).

The most common age-at-death estimation methods used in bioarchaeology and paleodemography are found in Standards (Buikstra and Ubelaker, 1994), which utilize the pubic symphysis, auricular surface, sternal rib end, and cranial sutures. These “traditional” approaches are often criticized for their inherent bias, but have created much of the data available for paleodemographic comparisons. Published age distributions for the Larson Site are based on Owsley and Bass (1979), which used Todd’s (1920) phases for the pubic symphysis. These data
were unavailable during this research, so age-at-death estimates for all adult skeletons were derived from the “traditional” approaches outlined in Buikstra and Ubelaker (1994).

Skeletons with preserved pubic bones, auricular surface, and/or cranial sutures were scored following criteria outlined in the Transition Analysis Age Estimation Skeletal Scoring Procedure Guide by Milner and Boldsen (2008). Transition Analysis was applied to all available adult skeletons with the pertinent skeletal indicators present. The full version of the ordinal scoring system can be found in Boldsen et al. (2002:96-104), Appendix 5.1. All scoring occurred prior to a full skeletal analysis of the individual to prevent the introduction of bias by observation of other morphological features associated with age. The scoring of individual components of a surface in this system, as opposed to an entire surface, maximizes the number of individuals available for analysis because fragmentary remains could be scored. The basis of the scoring method is much like other methods available that attempt to order morphological changes associated with age into stages. As such, “many of the terms are immediately recognizable as being derived from earlier work, especially that of McKern and Stewart (1957) and Lovejoy et al. (1985)” (Boldsen et al., 2002: 81). The author was trained on the scoring methods through the 2008 Workshop on Transition Analysis at the American Academy of Forensic Sciences Annual Meeting and through personal correspondence with Dr. George Milner. Additionally, this author has conducted other research using the Transition Analysis-based scoring method and the ADBOU computer program (Wilson and Algee-Hewitt, 2008; Shirley et al., 2009; Algee-Hewitt et al., 2010).

Age estimates were calculated through Transition Analysis, using the age estimation program ADBOU. ADBOU was originally developed by Roar Hylleberg and Jesper Boldsen
from the Anthropologica Database Odense, University of Southern Denmark. The program utilized in this analysis is Dr. Steve Ousley’s version available through Dr. George Milner’s website (http://www.anthro.psu.edu/projects_labs/bioarch/bioarch_lab.shtml), which is compatible with a Windows 7 platform. The ADBOU age estimation software uses a modified version of transition analysis. The first step of the Rostock protocol, which calls for the estimation of the probability of a certain age indicator given the age from the known age-at-death reference sample, was completed by Dr. George Milner and Dr. Jesper Boldsen (Boldsen et al., 2002). The weight functions were estimated by Milner and Boldsen using the Terry reference collection. The Terry collection comprises 1728 skeletons of known age, sex, ancestry, and cause of death from the St. Louis, Missouri area between 1920 and 1960 with age at deaths ranging from 16 to 102 years. These weight functions are built into the ADBOU program, which when combined with an appropriate prior (in ADBOU the choices are uniform, 17th century Danish, and CDC homicide data), calculates the age estimate for each individual. This method does not recover the parameters of the age-at-death distribution like other methods, so the mortality profile is not simultaneously estimated along with the individual age-at-death estimates. In this respect Transition Analysis is not truly “Rostock Compliant.” Figure 5.2 and 5.3 depict the typical output from two different individuals within the Larson sample. These individuals reflect one that has maximum amount of data available (see Figure 5.2), whereas as the other depicts one with little information available (see Figure 5.3). The different colored curves represent the age estimates from each age surface. The black curve represents the overall age estimate using the uniform prior and the blue curve represents the overall estimate using the 17th century Danish data as a prior. Of note, the age range in ADBOU is constrained from 15 to 110 years to reflect the entire adult mortality lifespan, so Figure 5.2 is truncated on the left side.
Figure 5.2. Exemplar output from ADBOU for a young individual with all age indicator data available.
Figure 5.3. Exemplar output from the ADBOU age estimation program for an older individual with missing data.
Transition Analysis seeks to rectify several issues with aging: effect of reference sample age distribution in the target sample, biases in age estimates, a means of combining information from different standard anatomical markers to produce a single age estimate and the difficulty of accurately and precisely aging the elderly. Transition Analysis prevents age mimicry of the reference sample’s mortality profile by regressing the observed morphological characteristics onto the age of the individuals (see Konigsberg and Frankenberg, 2002). A uniform prior probability \((f(a))\) for the distribution of age-at-death was chosen over the mortality data for four 17th century, rural Danish parish, because these data are inappropriate for prehistoric Native American and may not reflect the same population dynamics. The uniform prior is a more conservative approach when an appropriate prior is unavailable. The ADBOU program inputs the ordinal data from each skeleton into a logit regression model. A probability density of age is computed through Bayesian inference using the associated prior distribution, which in this research was a uniform prior. Each individual has a point estimate age-at-death with an associated 95% posterior density interval. It is important to note that all three surfaces do not need to be present to calculate an estimate; however, the width of the confidence interval increases when fewer scores are available.

A Bayesian Multifactorial approach was taken to incorporate the data from the traditional age estimation methods (Uhl, 2013). This method uses scores from the pubic symphysis (Brooks and Suchey, 1990), auricular surface (Lovejoy et al., 1985), and sternal rib end (Iscan et al., 1984 a,b) to calculate a Bayesian inferred point estimate and its associated 95% posterior density. Uhl et al. (2011) first suggested this method for use in forensic cases where anthropologists rely on traditional age-at-death methods heavily. This method was developed
through 1) testing the scores for each of the methods for the pubic symphysis, auricular surface, and sternal rib end to see if they followed a transition model and adapting the methods as necessary until they fit well to a cumulative log-probit model and 2) calculating the weights for the probabilities for each of the methods using the Judy Suchey’s Los Angeles County male forensic dataset. Since direct observation of Native American skeletons is diminishing, especially within the United States, it is imperative to test new methods that can incorporate previously collected data and determine their utility in studying population dynamics.

A relatively new method, suggested by Weise et al. (2008) and lauded by Milner and Boldsen (2012) as the way to approach age estimation is the Calibrated Expert Inference (CEI) method. Calibrated Expert Inference uses binary component scoring of several morphological traits that change with senescence to compute an age estimate. The CEI approach integrates several unpublished and under-published morphological features commonly employed by anthropologists to provide more precise age ranges. For example, this method focuses on traits, like vertebral lipping (Stewart, 1979), which have been used to narrow or shift age ranges in forensic skeletal analyses, but on their own are relatively uninformative. Definitions, a trait list, and suggestions on scoring were provided to the author by Dr. George Milner. These “non-traditional” traits provide data for when “traditional” indicators are not present or could be used in conjunction with them. Subjective scoring occurred as the last step in skeletal analysis to avoid biasing results using other methods. The best methodology for incorporating CEI data into a statistical framework and the “best” traits list has not been completed, so future research will assess their potential for computing age-at-death estimates, how they compare to Transition Analysis and Multifactorial approaches, and determine their influence on modeling mortality.
Population Dynamics

Multiple techniques were utilized to examine population dynamics within the Larson Site as this is the primary goal of paleodemography (Bocquet-Appel and Naji, 2006). The Larson Village demonstrates evidence of population decrease through settlement patterns and historic and ethnographic data suggesting spread of infectious disease throughout the Missouri River Basin. It is quite possible that demographic stationarity may be inappropriate, so the less restrictive assumption of population stability is assumed for the purposes of analysis (Wood et al., 2002). Assuming a stable population, following the ideas outlined by Lotka (1922), one is able to analyze how a change in one demographic parameter would affect the other parameters. Thus, the age-at-death data from the skeletal analyses can be used to determine the best fitting model to the Larson Village cemetery sample.

The point estimate for each individual was taken to represent each individual’s age-at-death to model the mortality within the Larson Village. The maximum likelihood point estimate from the ADBOU and Bayesian multifactorial methods were combined with the maximum likelihood estimates derived using Shackelford et al. (2012) and the average for the long bone lengths estimates for juveniles. The four datasets were compared to the average point estimate from the Owsley dataset. The overall age range was not incorporated into the mortality analyses to simplify analyses, but future work will need to account for the error in the models.

The raw point estimates from each dataset were plotted using the survival library and the survfit function in the R statistical programming language version 2.15.1. This function fits a nonparametric Kaplan Meier survivorship curve to the data and computes associated summary measures. This survival curve is a stepped curve that adds information as each death occurs, so reflects the entire age distribution of sample. As such, it provides a good basis for determining
the fit of a parametric model and if a subset within the population is significantly affecting the overall population mortality curve. The survivorship curves from all significant parametric models were visually compared to the Kaplan-Meier survival plots to determine fit. Unfortunately, like most analyses of the age-at-death, point estimates were used for initial model building, which assumes age-at-death is known with certainty (Konigsberg and Frankenberg, 2013).

**Modeling Mortality**

Three parametric hazard models, the Gompertz, the Gompertz-Makeham, and Siler models were tested to determine the best-fitting model for the entire age distribution using R version 2.15.1. The parameter values were computed through maximum likelihood estimation (Konigsberg and Frankenberg, 1994). Maximizing the likelihood accounts for the age uncertainty inherent in skeletal data (Frankenberg and Konigsberg, 2002).

Maximum likelihood is an iterative process in which the parameters are selected for the model. This process continues until it reaches a specified or global maximum in the likelihood function and the parameters best fit the data. Optimization to maximize the log likelihood of the model parameters was achieved using the generalized “optim” function in R with the finite scaling function set to -1, which maximizes the log likelihood. The “optim” function uses the Nelder-Mead simplex algorithm by default to optimize the user provided function. It is used over the optimx function, which has been proposed to replace the optim function, but literature has clearly shown the utility of the optim function (Konigsberg and Frankenberg, 2002). Starting values of 1.0e⁻⁶ were inputted into the “optim” function for each parameter estimate and adapted
as needed. A model was deemed successful if convergence was reached, a log-likelihood value was generated, and no warnings messages were given.

The log-likelihood values served as the basis for determining the fit of a model following Hilborn and Mangel (1997). The likelihood approach is often used in ecology for hypothesis testing to determine how well different models approximate reality (Hobbs and Hilborn, 2006). The model parameters that had the largest accompanying log-likelihood value were considered the maximum likelihood estimates for the model. The best fitting model’s parameters served as the basis for computing the mean-at-death, the crude birth rate, the mean age of the living, the relative hazard, survivorship, and probability density function for the age distribution.

Statistical significance between the model parameters was evaluated by comparing the log-likelihood values. A larger log-likelihood value indicated a better fitting model. In cases where the difference between two values was negligible, the model with the fewer parameters was chosen, since the best model is the one that is the most parsimonious (Wood et al., 2002). Differences between log-likelihoods of each model were tested for significance through the likelihood ratio test (Hilborn and Mangel, 1997). This ratio can be converted into an asymptotic Chi-square ($\chi^2$) and can be written as:

$$X^2 = -2(L_0 - L_1)$$

where the smaller the ratio the larger the $X^2$ will be (Agresti, 1996). For example, the log-likelihood from the three-parameter Gompertz-Makeham is subtracted from the comparable two-parameter Gompertz and multiplied by two (see Konigsberg and Frankenberg, 2002 for a
worked example). The resulting $\chi^2$ value was compared to the Chi-square distribution’s critical value (3.841) with degrees of freedom equal to the difference in the number of parameters which was one in this research. If a difference ($\chi^2$) was greater than the critical value the two models were deemed to be significantly different and the model with the larger log-likelihood value was chosen as the best model.

The best performing models’ parameters were used to compute the age-specific survival function ($S(a)$), the hazard/force of mortality function ($\mu(a)$) and the probability density function ($f_0(a)$) for each dataset. These functions were used to plot the survival and hazard curves and the probability density function for the four-parameter Siler model. The computation of one function allows the other two to be estimated using the data. Plotting of the survivorship function $S(a)$ demonstrates the proportion of a cohort of individuals starting at time 0 that is still alive at time $a$. The probability density function is the fraction of all deaths from initial cohort that are likely to occur at an instant of time $a$. This is the continuous time generalization of the discrete time age specific probability of death. The hazard is the instantaneous risk of death and is the negative of the first derivative of log survivorship at age $a$. Equivalently, it can be defined as the ratio between the density function and the survivor function at exact age $a$.

Life expectancy at birth ($e_0$) is a measure commonly used to evaluate the overall level of mortality in a given population. It incorporates both pre-reproductive and adult mortality, whereas life expectancy at adulthood (defined here as age 15 years) provides a measure of reproductive potential and adult longevity that controls for infant and childhood mortality. The life expectancies at birth ($e_0$) and at age 15($e_{15}$), the crude birth and death rate, and the mean age of the living were computed for the best model for each dataset using the data from the $S(a)$,
h(a), and f(a). O’Connor (1995) generated $e^0$ during a meta-analysis of skeletal samples from the New and Old Worlds and suggested a pattern of high fertility and mortality existed in many prehistoric societies. However, she found significantly lower values, ranging between 13 and 32 years for the estimates of $e^{15}$ (O’Connor, 1995). This could be interpreted as an age estimation bias or that young adult mortality is higher for prehistoric populations (O’Connor, 1995; McCaa, 2002). While in some cases the $e^{15}$ pattern may reflect a true difference between populations, it is probable that traditional skeletal age estimation techniques have biased estimates of life expectancy for prehistoric populations and truncated longevity estimates (Bocquet-Appel and Masset, 1982; Konigsberg and Frankenberg, 1992, 1994).

The crude birth and death rates are the inverse of the integral of survivorship and the mean age of the living is the integral of survivorship multiplied by age divided by the mean age-at-death. These relationships implicitly assume that the population was demographically stationary so that crude birth and death rates were equal.

**Juvenile Survivorship**

In order to investigate juvenile mortality in a comprehensive fashion several additional measures beyond the incorporation of the juvenile component into the parametric Siler hazard function were utilized. Most skeletal samples have issues of under-enumeration of juveniles, so several measures have been created to estimate the proportion of juveniles compared to adults, infants compared to older juveniles, and older adults compared to juveniles. Bocquet-Appel and colleagues (Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006; Bocquet-Appel and BarYosef, 2008) have used the proportion of sub-adults to suggest an increase or decrease in fertility. An increase in the proportion of sub-adults in a sample suggests positive fertility rates while a
decrease suggests negative fertility rates (Acsadi and Nemeresski, 1970; Buiskra et al., 1986; Bocquet-Appel, 2002). The first measure to examine fertility within the Larson population used the ‘Juvenile Index’ \( (15P_5) \), which is the proportion of children five to nineteen over individuals over the age of five \( (D_{5-19}/D_{5+}) \). Bocquet-Appel and Naji (2006) demonstrated that the \( 15P_5 \) was highly correlated to both the growth rate and crude birth rate in simulations using 45 Coale and Demeny (1966) pre-industrial life tables for stable populations. The \( 15P_5 \) measures for each dataset and associated raw data can be found in the following chapter.

The second measure of fertility, the \( D_{30+}/D_{5+} \) proportion, was calculated for each dataset using the equation \( k=\frac{N(N-1)}{2} \) with a 95% comparison interval (Buikstra et al., 1986), where \( N \) is the number of samples being compared, \( k \) is the number of comparisons. The comparison interval was computed using the following equation:

\[
CI = \frac{D_{30+}}{D_{5+}} \pm m_{.05,k,.00} \sqrt{\frac{.125}{D_{5+}}}
\]

, where \( m \) is derived from the Studentized maximum modulus table for a two-tailed test with an \( \alpha=0.05 \).

The \( D_{30+}/D_{5+} \) proportion of immature skeletons is the number of skeletons over the age of thirty divided by the number of skeletons over five years of age and older. This measure has a strong negative correlation with the birth and death rate when compared to data from 312 stable populations (Coale and Demeny 1966) and supports the Sattenspiel and Harpending (1983) argument that birth rate has a greater influence on mortality in a skeletal sample. For this
analysis, the number of samples is 5, so m is 3.114. A significant difference between datasets is considered if the comparison intervals do not overlap.

Likewise, the $D_{1.5}/D_{1.10}$ ‘Juvenile Death Proportion’ with the comparison interval outlined above, was computed for each dataset to provide further data on juvenile mortality. This proportion is the number of deaths from ages one to five divided by the number of individuals one to ten. It has a high positive correlation with birth rate and the juvenile death rate (Buikstra et al., 1986), which implies that a decrease in the proportion could indicate either a decrease in juvenile mortality or a decrease in birth rate. This was used in conjunction with information on the crude birth and death rates and other juvenile proportional measures to provide a better understanding of the population dynamics.

**Adult Mortality**

The analysis of adult mortality focused on the variability associated with sex-specific differences in age-at-death. These analyses included any individuals with an estimated age of fifteen years or above. The maximum likelihood point estimates of age-at-death from Transition Analysis and Multifactorial Analysis and the Owsley dataset were analyzed using the parametric Gompertz and Gompertz-Makeham models to determine if the age estimation methods caused different sex-specific patterns. It is important to be able to detect an age-independent factor affecting mortality, as previous research (Owsley, 1975) indicated a significant mean age-at-death difference between males and females and attributed this to the high risk of childbearing in pre-industrial populations.
CHAPTER 6  
Results

This chapter presents the results from the fertility and population growth studies, the Larson mortality profile for each of the five datasets, and the sex-specific adult mortality patterns. These results will serve as the basis for discussing how age-at-death methods affect interpretations of the population dynamics and will lead into discussing the paleodemography of the Larson Site.

Growth and Fertility
Since the age-at-death methods incorporated into this research have the potential to change the age at death distributions it is important to explore birth and growth rates and the proportion of juveniles (15P₅ proportion) and older adults (D30+/D5+ proportion) within each sample. Both measures provide rough estimates as to the directionality of population growth or decline and should not be interpreted as a direct reflection of the population’s birth or growth rate. These tests are typically applied in biased samples with juvenile under-representation (particularly for ages under five years), which is a non-issue in this research. The calculation of the proportional measures permits comparison with other populations that may reflect juvenile underenumeration that are found in the literature.

Table 6.1 presents the number of individuals 0-4 years, 5-19 years, greater than 5 years, the total sample size, and the juvenile index. The 15P₅ proportion ranges between 0.2544 to 0.5575. All datasets indicate a population that had high fertility levels. The juvenile proportion suggests a relatively high percentage of 5 to 19 year olds in the population, which in turn indicates a high crude birth rate. However, the juvenile index results were impacted by the
dataset used. Owsley’s data suggests the lowest juvenile index for the Larson Site, while the Multifactorial dataset indicates an extremely high index. Regardless of the age-at-death estimation method used for juvenile individuals, the $^{15}$P$_5$ ratio indicates a high percentage of juveniles in the sample. The Transition Analysis-based datasets indicate children and young adults comprise approximately 40% of the cemetery sample, while the Multifactorial method suggests that over half of the sample is comprised of individuals between 5 and 19. Both methods indicate more children than would be expected in a pre-industrial population. The Owsley dataset produced the lowest percentage of children and adults with only 26% of those over the age of 5 being in the child or young adult age range. The Owsley dataset is in line with other populations throughout North America when compared to Bocquet-Appel and Naji’s juvenile indices from 62 cemeteries representing the agricultural transition in North America (~7500 BP to 350 BP).

Table 6.1. The juvenile proportion ($^{15}$P$_5$) for each dataset in the Larson Site.

<table>
<thead>
<tr>
<th>Sample/ Aging Method</th>
<th>0-4 years</th>
<th>5-19 years</th>
<th>&gt; 5 years</th>
<th>N</th>
<th>$^{15}$P$_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal/Transition</td>
<td>358</td>
<td>97</td>
<td>243</td>
<td>612</td>
<td>0.3992</td>
</tr>
<tr>
<td>Dental/Transition</td>
<td>220</td>
<td>100</td>
<td>252</td>
<td>473</td>
<td>0.3968</td>
</tr>
<tr>
<td>Skeletal/Multifactorial</td>
<td>358</td>
<td>123</td>
<td>224</td>
<td>582</td>
<td>0.5491</td>
</tr>
<tr>
<td>Dental/Multifactorial</td>
<td>218</td>
<td>126</td>
<td>226</td>
<td>445</td>
<td>0.5575</td>
</tr>
<tr>
<td>Owsley</td>
<td>390</td>
<td>64</td>
<td>242</td>
<td>643</td>
<td>0.2644</td>
</tr>
</tbody>
</table>
Bocquet-Appel (2002) suggest that growth rate could be calculated through a regression using the $^{15}P_5$ index. Using his method, the growth rate for the Transition Analysis datasets ranged from 2.6 to 2.7 percent annually. The Multifactorial dataset, which had a reduced number of adults and a higher number of older adolescents, indicated a growth rate of 4.0-4.1% for the Larson Site, which is extremely high and unrealistic for a horticultural population. Conversely, the Owsley dataset, which had the highest number of 0-4 individuals, had the lowest growth rate at 1.2%. The Owsley dataset approximate growth rate is the only dataset that falls within the known, horticultural populations. A growth rate of 2 or 4% would be unrealistic for a horticultural population in the 18th century. More recently, Bocquet-Appel (2008) has retracted his statement that the growth rate can be approximated from the juvenile index and that it should be considered a “weak” indicator of population growth as Gage and DeWitte (2009) have argued. Furthermore, the divergence in the juvenile index within one population using different age-at-death methods supports the argument that the indices should only be used to suggest a trend within the population.

It appears that the age-at-death estimation method for adults significantly impacted growth rate and death rate calculations. The more juveniles versus adults increased the approximate growth rate. Using adult individuals, who only could be given an age range, eliminated many individuals that could be aged no more precisely than as an adult. This was apparent in the Multifactorial dataset, which required the most data to be available for scoring. The Transition Analysis datasets had the largest number of adults, but was still affected by the large number of juveniles.
The D30+/D5+ proportions provided an additional measure of population growth. Buikstra et al. (1986) suggest that populations with a higher number of older individuals indicate a population with a lower growth rate. When compared to the results from the juvenile index, the Transition Analysis dataset, which has a larger number of older adults, supports a lower growth rate than the juvenile index predicted. A higher juvenile index indicates a high growth rate, while a low D30+/D5+ proportion implies overall population growth. All datasets indicate some form of population growth, but not to the same levels as the juvenile index would imply. Thus, Larson had a high fertility rate, but did not see corresponding population growth as would have been predicted using the juvenile index. This is interesting, because the Arikara population as a whole was decreasing in the late 18th century.

Table 6.2 presents the total number of individuals 5 years and above, the D30+/D5+ proportion, and the 95% comparison intervals for the 5 datasets. The Owsley dataset has the highest proportion, while the Multifactorial/Skeletal dataset had the lowest proportion. No difference was seen in the Transition/Skeletal and Transition/Dental or the Multifactorial/Skeletal and Multifactorial/Dental datasets, which indicates that the juvenile age-at-death method had little impact on the D30+/D5+ proportion. The difference between datasets is the result of the adult age-at-death estimation method.

Overlap of the 95% comparison intervals indicates no significant difference between the D30+/D5+ proportions. No overlap exists between the Owsley and Multifactorial datasets, but both overlap the Transition datasets. The Owsley dataset overlaps at the higher end of the interval, while the Multifactorial dataset overlaps as the lower end of the interval. The Multifactorial dataset proportion suggests a population exhibiting population growth, while the
<table>
<thead>
<tr>
<th>Sample/ Aging Method</th>
<th>D5+</th>
<th>D30+</th>
<th>N</th>
<th>D30+/D5+</th>
<th>95% Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal/Transition</td>
<td>243</td>
<td>97</td>
<td>612</td>
<td>0.3992</td>
<td>0.3285-0.4698</td>
</tr>
<tr>
<td>Dental/Transition</td>
<td>252</td>
<td>97</td>
<td>473</td>
<td>0.3849</td>
<td>0.3155-0.4543</td>
</tr>
<tr>
<td>Skeletal/Multifactorial</td>
<td>224</td>
<td>58</td>
<td>582</td>
<td>0.2589</td>
<td>0.1853-0.3325</td>
</tr>
<tr>
<td>Dental/Multifactorial</td>
<td>226</td>
<td>57</td>
<td>445</td>
<td>0.2522</td>
<td>0.1790-0.3254</td>
</tr>
<tr>
<td>Owsley</td>
<td>242</td>
<td>118</td>
<td>643</td>
<td>0.4876</td>
<td>0.4168-0.5584</td>
</tr>
</tbody>
</table>

Owsley dataset would indicate a population with a relative decrease in growth. This is a product of the Multifactorial dataset having fewer adult individuals, so it actually has an underenumeration of adults compared to children. Also, less adult individuals were available to this author than in the initial demographic analyses for the Larson Site, which could account for the lower number of adults 30+ years of age in the Transition and Multifactorial datasets. The differences in sample size are not significant enough to suggest this resulted in the pattern. If population stability is assumed, the Larson Village was experiencing growth based on the $^{15}P_5$ proportions and the D30+/D5+. The Transition datasets do not indicate the high levels of population growth or decline as the other datasets suggest, but do indicate that the Larson Site may not be stationary, which is contrary to the archaeological and ethnographic literature. Thus mortality models that can handle a non-stationary population may be the most appropriate in understanding its demographic pattern.

Johansson and Owsley (2002) did not include data from the Larson Site when examining the overall health and mortality of the Upper Plains, because they believe that the abundance of juveniles in the sample would have skewed the results. A major argument for their actions was
the effect that the number of juveniles has on mean age-at-death. Mean-age-at-death has been
criticized as a measurement of population health, because it is easily skewed by elevated
juveniles or older adult individuals. A lower mean-age-at-death has been interpreted as indicating
elevated juvenile mortality. Since the number of juveniles is high for all age groups, but
specifically in the number of infants, juvenile mortality was examined using the D1-5/D1-10
proportion (Buikstra et al., 1986) in addition to mortality curves. Table 6.3 presents the percent
of individuals less than 1, individuals D1-D10, individuals D1-D5, the sample size, the D1-5/D1-
10 proportion, and the 95% comparison interval. A high D1-5/D1-10 ratio suggests relatively
high levels of mortality during early childhood. The Transition and Multifactorial datasets that
incorporated skeletal ages for juveniles had a lower proportion than the ones that incorporated
the dental ages for juveniles. The Owsley dataset had the lowest D1-5/D1-10 proportion overall.

The 95% comparison interval overlapped for all datasets. Also, the D1-5/D1-10
proportion indicated higher levels of juvenile mortality than the 15p5 proportion. This suggests
that another underlying factor may be affecting the Larson Site. Infant mortality was high,
young children appear to have a higher mortality rate, and older children and young adolescents
also appear to have a higher than expected mortality rate. These patterns will be evaluated
further through parametric mortality models.

The Larson Site cemetery does not have significant taphonomic or excavation biases
affecting sample composition that is pervasive in the bioarchaeological literature, so the large
number of juveniles in the sample cannot be used to justify the differences between the juvenile
indices. Thus, it appears that the Larson population had a high fertility rate and a high juvenile
mortality rate, which requires further exploration.
Table 6.3. Juvenile survivorship (D1-5/D1-10) for each dataset in the Larson Site.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>&lt;1 years</th>
<th>D1-D10</th>
<th>D1-D5</th>
<th>N</th>
<th>D1-5/D1-10</th>
<th>Interval</th>
<th>95% Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal/Transition</td>
<td>0.4608</td>
<td>131</td>
<td>94</td>
<td>612</td>
<td>0.7176</td>
<td>0.621-0.8137</td>
<td></td>
</tr>
<tr>
<td>Dental/Transition</td>
<td>0.3362</td>
<td>114</td>
<td>75</td>
<td>473</td>
<td>0.6579</td>
<td>0.5548-0.7610</td>
<td></td>
</tr>
<tr>
<td>Skeletal/Multifactorial</td>
<td>0.4845</td>
<td>129</td>
<td>93</td>
<td>582</td>
<td>0.7209</td>
<td>0.6240-0.8179</td>
<td></td>
</tr>
<tr>
<td>Dental/Multifactorial</td>
<td>0.3573</td>
<td>112</td>
<td>73</td>
<td>445</td>
<td>0.6518</td>
<td>0.5478-0.7558</td>
<td></td>
</tr>
<tr>
<td>Owsley</td>
<td>0.4261</td>
<td>103</td>
<td>58</td>
<td>643</td>
<td>0.5631</td>
<td>0.4546-0.6716</td>
<td></td>
</tr>
</tbody>
</table>

**Age-at-death methods and modeling mortality**

The following results present the mortality for the Transition/Skeletal, Transition/Dental, Multifactorial/Skeletal, Multifactorial/Dental, and Owsley datasets. These datasets represent a single cemetery population from the Larson Site and will be used to demonstrate how the age-at-death method can affect model choice and subsequent interpretations. The following results are organized by dataset.

**Transition Analysis-skeletal Dataset**

Table 6.4 presents the parameter estimates and corresponding log-likelihood values for the Gompertz, Gompertz-Makeham, and the four-parameter Siler models using the Transition-Skeletal dataset. The four-parameter Siler model outperforms the Gompertz and Gompertz-Makeham models, which can be explained by the incorporation of juvenile component, since nearly half of the site is comprised of juveniles. The Siler model parameters were used to compute the survivorship, hazard, and probability density functions. Figure 6.1 presents the non-
parametric Kaplan-Meier survival plot of the fitted age-at-death distribution for the Transition-
skeletal dataset. This dataset has a relatively gradual decrease in survivorship over time. A large
step is visible in the 10-20 year range. This corresponds to the fact that a large number of
individuals had the same calculated point age-at-death estimate in the 10 to 20 year age category
at 15 years, which is the constrained lower limit of the ADBOU ages. The population does
followed expected patterns of mortality (Gage 1990) in which there is steep drop in survivorship
in the very young, and leveling but continual decline in survivorship with a final low
survivorship for the very old. Figure 6.2 displays the best fitting four-parameter Siler, which
does not include the residual, adult mortality constant. This model follows the Kaplan-Meier
survival curve rather well. Gage (1991) has shown that the Siler model fits well with
populations which are believed to have an accidental, age-independent hump even without the $\alpha_2$
component. There is slight variability in the 10 to 20 year range, which the Siler model does not
entirely explain. Overall it conforms nicely. The Larson population is believed to have a high
number of young-adult females with a cause of death associated with child-bearing. Also,
typical risks of death, such as infectious disease, which were common in the protohistoric
Arikara, are going to affect certain age groups more than others, so they are also not age-
independent. Thus, the four-parameter Siler model provides a good model of mortality for the
Larson Site. The risk of death for the Larson Site, based on the Transition-skeletal dataset as
depicted in Figure 6.3, does not have the rapid increase in death with the advancing years as has
been shown with model life tables (Acsadi and Nemereski, 1970).
Table 6.4. Larson Site Transition-skeletal dataset Siler, Gompertz, and Gompertz-Makeham hazard model parameters.

<table>
<thead>
<tr>
<th>Transition/Skeletal</th>
<th>$\alpha_1$</th>
<th>$\beta_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$\beta_3$</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siler</td>
<td>0.5616</td>
<td>0.71649</td>
<td>N/A</td>
<td>0.0272</td>
<td>0.01745</td>
<td>-1263.434</td>
</tr>
<tr>
<td>Gompertz</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.134971</td>
<td>-0.0324411</td>
<td>-1483.118</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td>N/A</td>
<td>N/A</td>
<td>0.057543</td>
<td>4.65E-02</td>
<td>-0.0300003</td>
<td>-1505.253</td>
</tr>
</tbody>
</table>

*The best-fitting model is in bold.

Figure 6.1. Kaplan-Meier survival curve for mortality of the Larson Site using the Transition-skeletal dataset.
The expected pattern for age-specific force of mortality is a bathtub shaped curve in which a rapid increase in risk of death is associated with the older individuals. This is not seen in the Transition-skeletal dataset, because Transition Analysis has allowed for age-at-death estimates to be extended beyond that of other age-at-death estimations. Also, the hazard increases with advancing age at a low, steady pace. What is interesting in the risk of death curve is the short period of time at which risk at death is minimal. An expected pattern would have a fairly low hazard into adulthood and an increase with older adulthood. Rather this curve implies a low risk of death for individuals, who lived beyond age 10 with only a slight increase with age. Adults within the population had a similar risk of death. The theoretical age distribution, shown through the probability density function (PDF) in Figure 6.4, assuming a stationary population, indicates a high number of young infants and children until age 10 and a relative even distribution of individuals throughout late adolescence and adulthood.
Figure 6.2. The Larson four-parameter Siler survival curve with Kaplan-Meier plot for mortality based on the Transition-skeletal dataset. Red is Kaplan-Meier. Blue is fitted survivor curve.
Figure 6.3. The risk of death, hazard curve for the Larson Site based on the Transition-skeletal dataset.
Figure 6.4. Probability Density Function (PDF) for the Larson Site based on the Transition-skeletal dataset.
**Transition Analysis-dental Dataset**

Table 6.5 presents the parameter estimates and corresponding log-likelihood values for the Gompertz, Gompertz-Makeham, and the four-parameter Siler for the Transition-Dental dataset. The four-parameter Siler model was chosen as the best model. The Kaplan-Meier survival curve in Figure 6.5 indicates a rapid decline in survivorship with very young infants and children that slows at the 0.4 probability of survival. Also a step, as was seen in Figure 6.1, is seen in the late teens, which causes variation in the quality of the fitted Siler to the Kaplan-Meier curve. Survivorship continues to decrease with advancing age until it approximates zero as it approaches 70+ years. The Siler curve in Figure 6.6 fits the Kaplan-Meier curve well with slight variation between the fitted and expected in early adulthood. The hazard curve in Figure 6.7 corresponds well with the survivorship and highlights the lower risk of death in juveniles with dental age-at-death estimates over that which was seen in the Transition-skeletal dataset. This is most likely a product of the larger number of juveniles that could be aged using skeletal development. The risk of death decreases until around age 10 and increases slowly until age 40. The risk of death increased after age 40. Individuals over the age of 70 had the highest risk of death for adults, but it did not exceed the rate seen in the juvenile component. The PDF curve in Figure 6.8 highlights the large number of juveniles and the relative even distribution of adult individuals, which could be a product of choosing an uniform prior for the age-at-death distribution, but the uniformity in the curve starting around age 10 suggests otherwise. If the prior distribution was dominating the model the flatness of the probability density function should have started around age 15, the lower age-at-death limit in the ADBOU program. The juveniles are dominating the model and thus preventing interpretation of adult mortality.
Table 6.5. Larson Site Transition-dental dataset Siler, Gompertz, and Gompertz-Makeham hazard model parameters.

<table>
<thead>
<tr>
<th>Transition/Dental</th>
<th>$\alpha_1$</th>
<th>$\beta_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$\beta_3$</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siler</td>
<td>0.28096927</td>
<td>0.506172</td>
<td>N/A</td>
<td>0.02639577</td>
<td>0.0166527</td>
<td>-1099.261</td>
</tr>
<tr>
<td>Gompterz</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0845058</td>
<td>-0.0157024</td>
<td>-1196.808</td>
</tr>
<tr>
<td>Gompterz-Makeham</td>
<td>N/A</td>
<td>N/A</td>
<td>0.042247</td>
<td>0.03411197</td>
<td>-0.0220246</td>
<td>-1198.622</td>
</tr>
</tbody>
</table>

*best-fitting model in bold

Figure 6.5. Kaplan-Meier survival curve for mortality of the Larson Site using the Transition-dental dataset.
Figure 6.6. The Larson Siler survival curve with Kaplan-Meier plot for mortality based on the Transition-dental dataset. Red is Kaplan-Meier. Blue is fitted survivor curve.
Figure 6.7. The risk of death, hazard curve for the Larson Site based on the Transition-dental dataset.
Figure 6.8. Probability Density Function (PDF) for the Larson Site based on the Transition-dental dataset.
**Multifactorial-Skeletal Age Dataset**

Table 6.6 presents the parameter estimates and corresponding log-likelihood values for the Gompertz, Gompertz-Makeham, and the four-parameter Siler without the $\alpha_2$ parameter for the Multifactorial-Skeletal dataset. The Siler model and its parameters were used to compute the survivorship, hazard, probability density functions. The Kaplan-Meier age-at-death distribution, seen in Figure 6.9, has a step around 15 years of age that is even more significant than that which is seen in the Transition datasets. This drop is slightly a result of age lumping caused by the application of the Multifactorial adult age estimation method. This step causes slight variation between the fitted Siler model and the Kaplan-Meier curve as is seen in Figure 6.10. The hazard curve in Figure 6.11 reflects a high infant mortality rate that drops by 0.06 from 0 to 5 years. A slower, decreasing rate is seen until age 10 at which time the Larson Site has the lowest risk of death. From 10 years onward the risk of death steadily increases with a spike at age 60. The increase in the risk of death around age 60 and beyond relates to the terminal age category for the underlying methods within the adult component of the dataset based on the Multifactorial approach. Overall, the pattern of mortality follows a typical pattern for pre-industrial populations. The PDF curve seen in Figure 6.12 does not have an expected older age jump as would be expected if there is a spike in the hazard curve. The theoretical age distribution demonstrates a large number of infants, a decreasing number of children and adolescents, and smaller, fairly consistent distribution of all adults.
Table 6.6. Larson Site Multifactorial-skeletal dataset Siler, Gompertz, and Gompertz-Makeham hazard model parameters.

<table>
<thead>
<tr>
<th>Multifactorial/Skeletal</th>
<th>$\alpha_1$</th>
<th>$\beta_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$\beta_3$</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siler</td>
<td>0.59586</td>
<td>0.70324</td>
<td>N/A</td>
<td>0.02963</td>
<td>0.02919</td>
<td>-1142.942</td>
</tr>
<tr>
<td>Gompertz</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.1739717</td>
<td>-0.041979</td>
<td>-1325.196</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td>N/A</td>
<td>N/A</td>
<td>0.07439</td>
<td>0.060069</td>
<td>-0.038787</td>
<td>-1344.33</td>
</tr>
</tbody>
</table>

*best-fitting model in bold

Figure 6.9. Kaplan-Meier survival curve for mortality of the Larson Site using the Multifactorial-skeletal dataset.
Figure 6.10. The Larson Siler survival curve with Kaplan-Meier plot for mortality based on the Multifactorial-skeletal dataset. Red is Kaplan-Meier. Blue is fitted survivor curve.
Figure 6.11. The risk of death, hazard curve for the Larson Site based on the Multifactorial-skeletal dataset.
Figure 6.12. Probability Density Function (PDF) for the Larson Site based on the Multifactorial-skeletal dataset.
**Multifactorial-Dental Dataset**

Table 6.7 presents the parameter estimates and corresponding log-likelihood values for the Gompertz, Gompertz-Makeham, and the four-parameter Siler model for the Multifactorial-Dental dataset. The four-parameter Siler model and its parameters were used to compute the survivorship, hazard, and probability density functions. The Kaplan-Meier plot in Figure 6.13 follows a consistent pattern of survivorship, but with a significant downward step around the age 15, which is the lower age-at-death limit for adults using the multifactorial method. When looking at the dataset, the Multifactorial maximum likelihood estimates had a number of individuals with ages at 15.75. This is consistent with the other datasets that indicate several young adults in which the grouping in the dataset is affecting the survivor curve. This age differential is visible when the Siler survivor curve is fitted to the Kaplan-Meier plot as seen in Figure 6.14. The Siler model fits well, but exhibits variation between the Kaplan-Meier and the Siler curve in early adulthood. Another slight difference is the Siler model underestimates in the 35-50 age ranges. The hazard curve in Figure 6.15 corresponds well with the survival curve. The hazard curve demonstrates a high risk of death for infants, albeit slightly less compared to the Multifactorial-skeletal dataset, a decreasing hazard with age until it levels at the lowest risk of death at age 10, and starts to increase consistently until age 60. At age 60 it significantly increases, but does not exceed the rate of decline in the juvenile component. The PDF curve in Figure 6.15 also highlights the large number of infants in the dataset, which drops very quickly with the rest of the sample having a fairly even distribution across the ages.
Table 6.7. Larson Site Multifactorial-dental dataset Siler, Gompterz, and Gompertz-Makeham hazard model parameters.

<table>
<thead>
<tr>
<th>Multifactorial/Dental</th>
<th>$\alpha_1$</th>
<th>$\beta_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$\beta_3$</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siler</td>
<td>0.294499</td>
<td>0.518406</td>
<td>N/A</td>
<td>0.028644</td>
<td>0.03100284</td>
<td>-989.886</td>
</tr>
<tr>
<td>Gompterz</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.10251522</td>
<td>-0.0163668</td>
<td>-1069.304</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td>N/A</td>
<td>N/A</td>
<td>0.053599</td>
<td>0.04328103</td>
<td>-0.0279439</td>
<td>-1067.907</td>
</tr>
</tbody>
</table>

*best-fitting model in bold.

Figure 6.13. Kaplan-Meier survival curve for mortality of the Larson Site using the Multifactorial-dental dataset.
Figure 6.14. The Larson Siler survival curve with Kaplan-Meier plot for mortality based on the Multifactorial-dental dataset. Red is Kaplan-Meier. Blue is fitted survivor curve.
Figure 6.15. The risk of death, hazard curve for the Larson Site based on the Multifactorial-dental dataset.
Figure 6.16. Probability Density Function (PDF) for the Larson Site based on the Multifactorial-dental dataset.
**Owsley Dataset**

Table 6.8 presents the parameter estimates and corresponding log-likelihood values for the Gompertz, Gompertz-Makeham, and the four-parameter Siler model for the Owsley dataset. The four-parameter Siler was chosen to compute the survivorship, hazard, and probability density functions. The overall Kaplan-Meier survivor curve in Figure 6.17 follows a pattern fairly consistent with a typical human age pattern of mortality. However, the curve is more stepped than the other datasets, because the groupings of the same age-at-death for multiple individuals. The age-at-death estimates in the Owsley dataset have a pattern often seen in bioarchaeological literature, in which ages have five to ten year spans with most ages being rounded to the nearest 5 or 10, which when plotted exaggerate the step-nature of the Kaplan-Meier survivor curve. The original age-at-death categorization reflects the life table methodology. The Siler smoothed and fit the dataset well, as seen in Figure 6.18, but it does display some differences between the fitted and the Kaplan-Meier survival plot for the older child and adolescent ages. The hazard curve in Figure 6.19 supports the expected pattern for mortality in most known pre-industrial populations, which have a ‘boat-shaped’ hazard curve. The hazard curve indicates a high infant mortality, relatively low mortality for adolescents and young adults, and an very high risk of death for individuals over 40 years of age. This is supported by the PDF curve for the Owsley dataset in Figure 6.20 and demonstrates a high number of infants and young children compared to the rest of the sample and a slightly higher number of individuals in between 30 and 40 years of age. After the age 45 the PDF is nearly zero. Unlike the other datasets, an older age hump was clearly visible, albeit small.
Table 6.8. Larson Site Owsley dataset Siler, Gompertz, and Gompertz-Makeham hazard model parameters.

<table>
<thead>
<tr>
<th>Owsley</th>
<th>α1</th>
<th>β1</th>
<th>α2</th>
<th>α3</th>
<th>β3</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siler without α2</td>
<td>0.262367013</td>
<td>0.26978</td>
<td>N/A</td>
<td>0.0003106</td>
<td>0.1009104</td>
<td>-1315.292</td>
</tr>
<tr>
<td>Gompertz</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.09952134</td>
<td>-0.020301</td>
<td>-1465.827</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td>N/A</td>
<td>N/A</td>
<td>0.048635</td>
<td>0.0392733</td>
<td>-0.025355</td>
<td>-1472.196</td>
</tr>
</tbody>
</table>

*best-fitting model in bold

Figure 6.17. Kaplan-Meier survival curve for mortality of the Larson Site using the Owsley dataset.
Figure 6.18. The Larson Siler survival curve with Kaplan-Meier plot for mortality based on the Owsley dataset. Red is Kaplan-Meier. Blue is fitted survivor curve.
Figure 6.19. The risk of death, hazard curve for the Larson Site based on the Owsley dataset.
Figure 6.20. Probability Density Function (PDF) for the Larson Site based on the Owsley dataset.
**Comparison of Methods**

When the survivorship curves for all datasets are plotted on one graph, as is seen in Figure 6.21, certain trends are apparent. The Owsley dataset follows the expected pattern based on model life tables, while all of the other datasets indicate a lower survivorship for all adults, including those in the young adult range. Also, a difference between the datasets that incorporated dentition versus skeletal growth are visible. Juveniles with age-at-deaths from dental mineralization scores had a greater age-specific survivorship compared to the juveniles with age-at-deaths derived from skeletal development.

Corresponding to the differences in the survivorship curves, differences are visible in the instantaneous risk of death curves in Figure 6.22. The dataset-specific hazard curves indicate high mortality for infants and young children under age eight. The adolescent and young adult risk-of-death vary as a result of the age-at-death method used to create the dataset. The Owsley dataset is almost identical to the expected U-shaped hazard curve expected in pre-industrial populations. However, the multifactorial and transition analysis based datasets are more likely representative of reality as they both incorporate older individuals into model estimation.

The probability density functions for all datasets have the most interesting pattern, because the amount of juveniles in the Siler model is causing them to dominate the mode, which prevents interpretation of the adult component. Based on the flatness of all of the probability density function in Figure 6.23, it would be assumed that the living population had a similar amount of adolescents, young adults, and older adults. Based on the other methods utilized in this research, this is not the case. Further exploration is needed to understand the patterning and possibility the implementation of other mortality models.
Figure 6.21. Survivorship curves for all five datasets from the Larson Site.
Figure 6.22. Hazard curves for all five datasets from the Larson Site.
Figure 6.23. Probability density functions for all five datasets from the Larson Site.
**Demographic Measures**

The best-fitting four-parameter Siler model was used to calculate basic summary demographic measures such as mean-at-death, mean age of the living, and crude birth rate (which also implies crude death rate). Table 6.9 provides the summary statistics for these measures for each of the datasets and also includes the mean age-at-death and crude birth rate calculated by Owsley (1975) and published in Owsley and Bass (1979). The mean age-at-death for all datasets is fairly low implying a young population. The Owsley dataset had the highest mean age-at-death, while the Multifactorial-skeletal had the lowest. Interestingly, the mean age of the living was different. The Transition-dental dataset produced the highest mean age of the living at 20.78 years and the Multifactorial-dental dataset produced the lowest at 14.29 years. The dataset did significantly impact the demographic measures derived from the model. The Multifactorial-based datasets produced results similar to the Owsley dataset and the published measures (Owsley and Bass 1979). The Transition Analysis based datasets suggest a slightly older but still young population. The lower mean ages for the living and deceased correspond to the relatively high crude death rate. The crude death rate figures range from 6% to near 10%. Correspondingly, the crude birth rate also ranges from 6% to 10%. In order to accept the Larson Village was stationary, there had to have been a high fertility rate followed by a high death rate, which I do not believe to be the case. This population was most likely declining based on the high number of juveniles, the low mean-at-death estimates, and the relative lack of adults. Thus, models that do not assume stationarity like that used in this research need to be utilized to better understand the demographic patterns within the Larson Site. The four-parameter Siler model was the best fitting model for all datasets and modeled the data well. A timing and rate of decline in the juvenile component between the different datasets is apparent.
The datasets that included juveniles aged through dentition had a lower initial risk of death and a less-steep curve associated with infant survivorship. The datasets that included skeletal ages for juveniles have a much higher initial risk of death with a very steep and rapid decline in survivorship. The juveniles with skeletal-based ages appeared to have a greater risk of death than the juveniles with dental-based ages. Also, the datasets with dental ages had a lower survivorship and PDF for the younger age groups compared to those with skeletal ages. The datasets with dental ages had fewer juvenile individuals overall, which could be causing this pattern. Likewise, the timing and rate of decrease in older adult survivorship and the increase in risk of death were affected by the age-at-death estimation method. Transition Analysis age-at-death methods extended the estimated ages at death for most adults beyond what the traditional age-at-death methods could. As a result, the hazards increased, but not to the significant levels causing the right side of the expected ‘bathtub’ shaped hazard curve to be almost non-existent. The Multifactorial datasets and the Owsley dataset exhibit the relative steep increase with the

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Model</th>
<th>mean age at death</th>
<th>crude death rate</th>
<th>mean age of living</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal/Transition</td>
<td>without α2</td>
<td>11.98</td>
<td>0.083</td>
<td>18.71</td>
</tr>
<tr>
<td>Dental/Transition</td>
<td>without α2</td>
<td>16.62</td>
<td>0.0601</td>
<td>20.78</td>
</tr>
<tr>
<td>Skeletal/Multifactorial</td>
<td>without α2</td>
<td>10.01</td>
<td>0.0999</td>
<td>15.25</td>
</tr>
<tr>
<td>Dental/Multifactorial</td>
<td>without α2</td>
<td>12.18</td>
<td>0.0821</td>
<td>14.29</td>
</tr>
<tr>
<td>Owsley</td>
<td>without α2</td>
<td>13.096</td>
<td>0.0761</td>
<td>15.075</td>
</tr>
<tr>
<td>Owsley (1975)</td>
<td>-</td>
<td>13.73</td>
<td>0.0723</td>
<td>-</td>
</tr>
</tbody>
</table>
advancing age, the right side of the ‘bathtub’, which would be expected based on the literature (Wood et al., 2002). Regardless of the method used to estimate age, a few overall trends can be seen for the Larson Site. There is a high infant mortality rate in which children under the age of 5 years had a high risk of death. This risk of death rapidly decreased where those that lived beyond age 10 years had a similar risk of death into adulthood. This was followed by a small increase in risk with advancing years. The fact that the probability density functions, which relates to the expected age-at-death distributions, are very similar from adolescence through late adulthood indicate that some force of mortality is affecting the population in a similar way that may not be age-related. The Larson Cemetery represents a young population if mean age-at-death and mean age of the living are considered. Transition Analysis datasets suggest an older age for the living population compared to the other datasets. High crude and death rates are seen across all datasets indicating that the population dynamics of the Larson Village are more complex than would be assumed.

**Sex-Specific Mortality in the Larson Site.**

The Gompertz and Gompertz-Makeham models were fitted to the adult component for each of the Transition Analysis, Multifactorial, and Owsley datasets in order to determine if any sex differentials in mortality existed within the population. The results from the Transition dataset will be the focus of the discussion section. Table 6.10 presents the results from Gompertz and Gompertz-Makeham for the adults within the Larson Site. The Gompertz model fit well for all three datasets for male groups and was significant for the Transition Analysis and
Owsley datasets for females. The Gompterz-Makeham was the better model for the Multifactorial females.

Figure 6.24 displays the Kaplan-Meier survival curves by sex for the Transition Analysis dataset. Males have a higher survivorship compared to females prior to age 40, but after age 40 females have a slightly higher survivorship. The life-expectancy at age 15, based on the Gompertz parameters is 34.9 years for males and 33.5 years for females. Even though a variation in survivorship exists between males and females the overall estimated life expectancy was nearly equal.

The survivorship pattern derived from the Gompertz model is different for males and females as seen in Figure 6.25. Survivorship for females declines steeply from age 15 to age 30 and then declines at a slightly slower pace. Male survivorship declines steadily from age 15 to 40 at which point it starts to level and decrease at a much slower pace.

The Multifactorial dataset indicated a clear sex differential in the Larson Site as well. The sex-specific Kaplan-Meier survival curve in Figure 6.26 demonstrates this difference. As seen in figure 6.27, a similar pattern of survivorship as is seen in the transition analysis dataset in which females had lower survivorship until around age 40 followed by a higher survivorship after age 40 compared to their male counterparts. The life expectancy at adulthood for males within this dataset was 28.0 years, while life expectancy for females was 18.9 years. The same pattern is visible on the survivor curve as that seen in the Transition Analysis dataset. Males have a higher survivorship in early adulthood and females have a slightly higher survivorship after age 40.
Table 6.10. Larson Site sex-specific Gompertz and Gompertz-Makeham hazard model parameters for adults from the Transition, Multifactorial, and Owsley datasets.

<table>
<thead>
<tr>
<th></th>
<th>Transition Analysis</th>
<th>α1</th>
<th>β1</th>
<th>α2</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Males N=93</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gompertz</td>
<td></td>
<td>0.00845</td>
<td>0.043368</td>
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<td>-186.4851</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td></td>
<td>1.34E-02</td>
<td>-1.73E-02</td>
<td>1.08E-02</td>
<td>-204.21</td>
</tr>
<tr>
<td><strong>Females N=88</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gompertz</td>
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<td>0.01109</td>
<td>0.03596</td>
<td>N/A</td>
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</tr>
<tr>
<td>Gompertz-Makeham</td>
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<td>1.35E-02</td>
<td>-1.74E-02</td>
<td>1.09E-02</td>
<td>-196.62</td>
</tr>
<tr>
<td><strong>Multifactorial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Males N=77</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Gompertz</td>
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<td>0.0066</td>
<td>0.07592</td>
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</tr>
<tr>
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<td>0.00205</td>
<td>-3.51E-02</td>
<td>3.65E-09</td>
<td>-148.3404</td>
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<tr>
<td><strong>Females N=75</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gompertz</td>
<td></td>
<td>0.01042</td>
<td>0.05381</td>
<td>N/A</td>
<td>-152.3018</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td></td>
<td>2.34E-02</td>
<td>-2.51E-02</td>
<td>7.11E-11</td>
<td>-159.2757</td>
</tr>
<tr>
<td><strong>Owsley</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Males N=83</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gompertz</td>
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<td>0.00108</td>
<td>0.126976</td>
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<td>-106.7806</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td></td>
<td>1.16E-02</td>
<td>-1.49E-02</td>
<td>0.00934</td>
<td>-141.8262</td>
</tr>
<tr>
<td><strong>Females N=100</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gompertz</td>
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<td>0.00027</td>
<td>0.17764</td>
<td>N/A</td>
<td>-110.4502</td>
</tr>
<tr>
<td>Gompertz-Makeham</td>
<td></td>
<td>1.34E-02</td>
<td>-1.72E-02</td>
<td>0.01083</td>
<td>-185.2883</td>
</tr>
</tbody>
</table>
Figure 6.24. Sex specific Kaplan-Meier survival curve for the Larson Site using the Transition Analysis dataset.
Figure 6.25. Gompertz survival curves for adult males and females over the Kaplan-Meier survivorship from the Larson Site using the Transition dataset.
The clear sex differential is apparent when examining the adult survivorship using the Owsley dataset. A sex difference is suggested in the sex-specific Kaplan-Meier survival curve for the Owsley dataset as shown in Figure 6.28. This is even more apparent in the Gompertz survival curves for males and females compared to the overall Kaplan-Meier survival curve, but this trend may be exaggerated by the lack of older individuals within the dataset as seen in Figure 6.29. The pattern indicating a reversal in age-specific risk of death after age 40 that was visible in the multifactorial and transition datasets is not visible in the Owsley dataset. However, like the Transition Analysis dataset, no difference was found between the life expectancies. Owsley females’ expected age at death is 33.3 and males’ is 33.4.

The Kaplan-Meier models for adult mortality consistently demonstrate a difference in the male and females regardless of the age-at-death estimation method. The survival curves indicate females had a lower average age at death. However, the significance between male and female average age-at-deaths vary depending on the age-at-death method used to create the dataset. Overall, it appears that females had an increase in risk of death in early adulthood, but females that survived to older age had a lower risk of death compared to their male counterparts. Significant overlap exists between the male and female confidence intervals, but a trend in a sex differential in mortality is visible. Males and females did not have a difference in life expectancy at birth, but may have experienced a different pattern in adult age-specific survivorship, which requires more research.
Figure 6.26. Sex specific Kaplan-Meier survival curve for the Larson Site using the Multifactorial dataset.
Figure 6.27. Gompertz survival curves for adult males and females over the Kaplan-Meier survivorship from the Larson Site using the Multifactorial dataset.
Figure 6.28. Sex specific Kaplan-Meier survival curve for the Larson Site using the Owsley dataset.
Figure 6.29. Gompertz survival curves for adult males and females over the Kaplan-Meier survivorship from the Larson Site using the Owsley dataset.
CHAPTER 7
Discussion

The goal of this analysis was 1) to determine if hazard methodology would provide a significantly different mortality profile than that which was published for the Larson Site by Owsley and Bass (1979), which utilized life table methodology to obtain parameter estimates, and 2) to determine if new age-at-death methods developed after the initial demographic analysis of the Larson Village in the early 1970s impact the mortality profile of the population and any subsequent interpretations.

Age-at-death distributions
Although age-at-death distributions are not a recommended approach for analysis, the age-at-death distributions from each dataset were produced to allow for comparability with previous research. The pattern of mortality is very similar between the datasets. The age-at-death distributions for each dataset can be found in Appendix 1. The reason why a major difference is not apparent in the age-at-death distributions is that these distributions are using individual ages, which omits the error associated with the estimate. Traditional methods provide little information about inherent error in distributions of individual age estimates, so give the appearance of being more precise.

Datasets that used dentition as the age-at-death estimation method for juveniles produced higher mean age-at-death estimates, but did not have the same effect on the mean age of the living. The dental ages were consistently older than the skeletal ages, especially for the very young. When these ages were incorporated into the hazard models, the survivorship curve for individuals with dental ages started out lower than those with skeletal ages. More juveniles were
incorporated into the skeletal dataset with many of these reflecting the neonatal component of the skeletal assemblage, which did not have teeth associated with the remains. The fact that the teeth represented slightly older individuals and there were fewer individuals with teeth caused the shift in the survival curves. The Transition-dental, multifactorial-dental, and Owsley datasets produced similar survivorship and hazard curves for the juvenile component. Dental ages for Arikara indicate a lower starting survivorship and a less steep slope in the decrease in survivorship within the first year of life. Researchers have noted long bone growth variation in Arikara and attributed this to the environmental sensitive of skeletal growth (Merchant and Ubelaker, 1977; Jantz and Owsley, 1984; Jantz and Owsley 1985). Merchant and Ubelaker (1977) demonstrated that the growth curves resulting from different aging methods tend to be as different as if they were derived from two distinct populations. The deciduous dental development was advanced compared to Whites, which was interpreted as the dental ages being greater than the chronological age (Jantz and Owsley, 1984). These authors also established a temporal trend in long bone growth that indicated longer bones in Postcontact Coalescent Arikara juveniles than the same age counterparts earlier, but a decrease in lengths with the Disorganized Coalescent Arikara. The change in length with the latter groups was not uniform for all bones, which questions the overall trend. The pattern changing of skeletal growth within the Arikara indicates that age-specific growth rates within Arikara would affect the age-at-death estimate. This would indicate that the more stable dental ages are the most appropriate to use in paleodemographic studies of the Arikara and that skeletal age should not be substituted for when the dentition is unobservable.
The most significant difference between the hazards was in the adult age component of the mortality curves. As this research demonstrates, the age-at-death estimation method utilized impacts demographic parameter estimates. The dataset that incorporated Transition Analysis produced mortality curves that extended well into older adulthood and well beyond that which was produced from the Owsley or the Multifactorial-based datasets. Nagaoka and Hirata (2007) demonstrated that the application of MLE and Bayesian methods for age-at-death estimation using a Japanese population affected the distribution, the demographic measures, and life tables parameters. The MLE and Bayesian methods produced ages more consistent with older individuals where the traditional methods may be underestimating. Unlike Nagaoka and Hirata (2007), who observed no difference in average age-at-death between methodologies, this research found a significant difference between the phase-based methods used in the Owsley dataset and the Transition Analysis methods used in the Transition datasets. The incorporation of the older ages did affect the average age-at-death.

The survivor and the hazard curve for the Owsley dataset, which used Todd (1920) standards to produce the adult age-at-death estimates displayed several distinct steps in the survivor curve. These steps reflect the lumping common in older age-at-death methods in which the ages were rounded to end in a 5 or 0. Also, the Owsley curves displayed a steep drop in survivorship and a sudden, spike in hazard of death at the age of 45 years. This corresponds with the aging method’s terminal phase of 50+ years. The hazard curve implies that the population did not contain individuals beyond this age, which is unrealistic. Also, the rate of the hazard at the terminal phase is greater than that of the juvenile component. This has been indicated a normal appearance to a pre-industrial population based on model life tables (Coale and Demeny,
1983), but the hazard is more parabolic than hyperbolic. A hyperbolic curve to the adult hazard would be more congruent with a living population.

The Multifactorial datasets, which incorporated multiple phase-based approaches through maximum-likelihood, improved the adult component of the hazard and survivor curves. The Multifactorial had a greater shift in survivorship rates in the late adolescent/young adult period. This was the result of many of the age estimates having point estimates approximately 15 years. The method caused a lumping in the younger adult age category that was not as significant in the other datasets. The Multifactorial also saw a lumping in the older age range, which was a product of the underlying age-at-death methods used. The terminal age range for the Multifactorial ages was 60+, which corresponds to the slope of the hazard curve increasing at 60 years. The Multifactorial method alleviates some of the reference sample bias obvious in the Owsley dataset, because accounts for older individuals and improves upon the interpretability of the mortality within the older individuals within the cemetery sample. Even though the multifactorial method was strictly aimed at the forensic community to estimate an age-at-death on an individual basis and select an appropriate prior age distribution, it does provide reasonable age-at-death estimates in bioarchaeological context. Unfortunately, it does not conform to the Rostock protocol. It can be an appropriate method when re-assessment of skeletal material is not possible. The Transition Analysis results support the utility of this component based multifactorial method in paleodemographic analyses. It does have limitations, such as the need to rescore skeletal material, and does not use all available age-indicators available. The application of Uhl et al.’s (2011) multifactorial method demonstrates that a multifactorial analysis based on transition analysis and incorporates sternal rib ends can be applied to
paleodemographic analyses. The foundation for Transition Analysis follows much of the Rostock protocols, eliminates much of the inherent reference sample bias, and can utilize the maximum amount of data compared to the other methods in this research. In particular, curves from the survival analyses extended beyond that which was suggested from the Owsley dataset and did not indicate a sudden drop in the age-specific survivorship or the risk of death; rather, it had a gradual decline in the slope. An increase in the risk of death is apparent after the age of 40 but does not indicate a complete dying-off of the population as one would interpret from the published data available for the Larson material. Also, the Transition Analysis datasets incorporated more adult individuals, which was a major limitation of the Multifactorial methods that require complete skeletal indicators for scoring.

**Mortality in the Larson Site**

It is nearly impossible to find a perfect model to fit all of the patterns of human mortality. A plethora of models have been suggested but tend to not fit the entire mortality pattern, are over-parameterized, or lack interpretability (Gage and Mode, 1993). The Siler model used in this analysis provided an excellent fit to all of the different age-at-death datasets without compromising utility in understanding the overall pattern of mortality. Consistent with previous analyses, the Larson Site had a high number of infants and young children. Larsen (1997) indicates that a larger number of children implies a higher fertility and an increase in individuals in a population. The under-five age category comprises almost one-third of the entire dataset, which suggests an increase in frailty within this age category. An overall increase proportion of juveniles in the population caused the lower mean-at-death. Life expectancies derived from all datasets were low, ranging from 10 to 16 years. A lower mean age-at-death at birth has been
interpreted as an elevated juvenile mortality level and a general decline in health (Goodman et al., 1984; Goodman et al., 2002). Others have argued that mean age-at-death is not a good indicator of population health due to sample bias, as this could be the result of the poor preservation of adult skeletal material. Gurven and Kaplan (2007) demonstrate that infant mortality values account for 56% of the variation in life expectancy at one year of age and 52% in the age-independent category, so demographic analysis cannot stop with life expectancy tabulations. Regardless, examination of the juvenile proportion (Buikstra et al., 1986) supports a high proportion of juveniles, not just those younger than five. In fact the juvenile index for all datasets was relatively high and approached the approximate 75% level that implies high levels of mortality for early childhood.

The availability of resources could explain much of the juvenile component. Nutrition, resource acquisition, and overall food supply are considered to be major factors in patterns of mortality over time (Gage and O’Connor, 1994). Food and nutrition are believed to be the cause for the historical decline in mortality and the epidemiological transition in causes of death from infectious disease to degenerative disease (DeWitte and Gage, 2009). Also, this idea serves as the basis for the increase in population size associated with the transition to agriculture, because the greater access to food permitted population growth. Nutrition can also be used to explain the short life expectancies and the high risk of death for pre-industrial horticultural populations. These populations were greatly affected by seasonal changes and resource changes. Archaeological evidence indicates the Arikara moved approximately every 30 years when local resources would have been diminished (Ewers, 1968). Records indicate that the Arikara were nutritionally deficient due to crop failure just prior to the smallpox epidemic in 1837-1838.
(Trimble, 1994). The late 18th century Arikara at Larson could have had diminished nutritional resources that would have affected their risk of death during an infectious disease epidemic. Also, several researchers have noted skeletal indicators of respiratory illnesses in different Arikara sites with many of the affected skeletons being juveniles (Palkovich, 1983; Kelley et al., 1994). Kelley et al.’s (1994) analysis on the rate and patterning of periostitis on the visceral surface of the ribs in the Larson, Sully, Mobridge, and Leavenworth populations suggest tuberculosis and/or pneumonia were prevalent in the 18th century along with the smallpox, measles, and treponemal infections.

Utilizing the Transition Analysis-dental dataset as the basis for this discussion would suggest that the mean age-at-death for the Larson population was 16.6 years and the mean age of the living was 20.8 years. This is much higher than the 13.2 life expectancy value suggested by Owsley and Bass (1979). A lower age-at-death indicates a population with a lower overall health, because an increase or decrease in average age-at-death has a close relationship to improvements or declines in health (Larsen, 1997). The higher life expectancy value produced in this research is a primarily a result of the age-at-death methods. Transition Analysis performs well for estimating ages of older individuals, which extends the mortality curve beyond what was possible with traditional methods. Also, the crude death rate is 60 per 1000 whereas Owsley and Bass (1979) suggested a crude death rate of 76. They state that the crude death rate is in accordance with the archaeological literature that the Arikara experienced a rapid decline during the post-contact period. The crude death rate calculated in this research is closer to that of Leavenworth’s rate of 63, which is a population known to have been in decline. Prior research suggested that the death rate exceeded the fertility rate, which this research does not support.
McCaa (2002) study using data available through the Western Hemisphere database suggests that fertility rates were high for most populations into the 19th century, but a demographic transformation began 500 years ago in the Americas with the intrusion of the Old World into the New World. The data presented indicates a relatively high fertility rate, which is in line with comparable Native American populations in the New World (Bocquet-Appel and Naji, 2006). In a low fertility population, the average age in the population will be higher and will have a rectangular shape instead of the pyramid (McCaa, 2002), which is not being seen in the Larson Site. The pattern in mortality indicates a high fertility rate and juvenile mortality rate, but a relatively stable mortality rate once adulthood is reached. Without examining the juvenile component more closely, the reasons for the high mortality rate cannot be elucidated.

The basic demographic statistics outlined here do not indicate a population in decline, but one that is similar to neighboring Arikara groups and other Native American populations. The Larson Village may have been affected by the increase in European presence, but the documented decline in numbers cannot be explained through the crude fertility or death rates. Other evidence of population decline is found archaeologically (Holder, 1970). The post-contact Arikara sites of the late 17th and 18th centuries demonstrate a reduction in house size and shifting of the fortification ditches to smaller spaces (Holder, 1970). The short length of the Larson Village occupation may be obscuring temporal trends found at the multi-component sites of Sully and Mobridge, which have longer village occupation lengths. The high number of juvenile indicate a high fertility rate. If the population was in decline, the expected model would have fewer juveniles than older adults. Either way, models like the one utilized in this research that assumes a stationary population may not be appropriate. The representativeness to the living
population does not seem to be a problem in the Larson Village. Rather, stationarity or the lack thereof is a viable explanation for the variation, so other models that incorporate growth and decline should be examined.

Palkovich (1981) indicates that the Arikara were hit by smallpox epidemics during the early 18th century, but little demographic evidence for population decline exists between 1680 and 1740 (Johansson and Owsley, 2002). Johansson and Owsley (2002) used 273 Arikara skeletons from 5 sites dating between 1250 to 1750, but did not include the Larson Site because of the large number of juveniles. The mean age-at-death for the collection was 19 years, which would have decreased to 13.2 years if Larson was incorporated into the sample. The data from this research indicate the mean age-at-death is much closer to the 19 years from the other sites examined in Johansson and Owsley (2002). Owsley and Bass (1979) state that archaeological data indicates that initial contact with European traders in the Upper Missouri improved the Native American welfare and stimulated population growth. Johansson and Owsley argue that intertribal conflict created by expansion of the Europeans, caused the major population decline in the Upper Plains instead of the exposure to pathogens. Johansson and Owsley (2002) contend that after 1740, inter-tribal conflict increased, with evidence from the Larson Village (Owsley et al., 1979), which was a major cause of the population decline. Furthermore, they imply that in the beginning of the 18th century the Arikara were increasing in size based on village size, midden deposits, and food storage facilities (Owsley, 1994), and that evidence for population decline is not supported archaeology until 1760-1780. Written descriptions support this decline in the late 18th century. References state that only seven villages remained containing about 900 warriors, which translates to approximately 3600 to 4500 individuals (Owsley and Bass, 1979).
Additionally, Owsley (1975) stated that the demographic data support a hypothesis that the population was infected by smallpox and that the error from the normal population vital statistics is caused by the inclusion of epidemic-produced mortality. Trimble (1994) provides a good historical correlate to what may have occurred in the 1870-1871 time period. The smallpox epidemic of 1837-1838 completely de-stabilized the Native American populations of the Upper Missouri River in which one half of the Arikara were believed to have died (Abel, 1932). Observations of the living conditions of the semi-sedentary tribes described them as crowded and unsanitary, which increased the virulence of the disease compared to their more nomadic counterparts. The epidemic completely destabilized the socio-political structure and permanently altered the culture of the Northern Plains Indians and led to the coalescence of the remaining horticultural peoples from the Hidatsa, Mandan, and Arikara (Trimble, 1994).

The Larson Site cemetery could very easily represent an epidemic population. Epidemic populations have a very similar age distribution to that of the living. Signoli et al. (2002) examined the remains from a cemetery in Southern France that was associated with the 1722 plague outbreak and found in their research that the skeletal based demographic profile was similar to 18th century census documents. Others have indicated that an epidemic that is not selective in sex or age would produce a skeletal assemblage that reflects a normal living population (DeWitte, 2009). Palkovich (1981) suggested that the epidemics can uniformly increase mortality in a population, but with age-specific risks. She continues in stating that a series of outbreaks can cause a major reduction in the number of individuals surviving to adulthood. Since mortality is selective, a normal cemetery population should reflect those with the highest level of frailty (Vaupel, 1979). Individuals that are young, old, malnourished, or
diseased have a greatest risk of death and are more likely to be found in a normal cemetery population. It would be expected to find mostly the young and old in a cemetery with a few individuals representing the age-independent accident-related deaths. The Larson Cemetery has a high number of juveniles 10 years of age and under and a relatively uniform number of adults. This pattern is similar to what other have found in cemeteries associated with the Black Death (Paine, 2000; Margerison and Knusel, 2002). However, when compared to the catastrophic pattern, the Larson population had a much lower frequency across the lifespan in the theoretical age-at-death profile. According to ethnographic data, the Arikara left the village for long periods of time throughout the year for hunting and trading leaving the young, old, and incapacitated in villages (Hurt, 1969). In reality, a normal mortality scheme for the Larson Cemetery should not reflect a living population. The Larson Site does not reflect a normal living age distribution, which raises etiological questions that can only be answered through the incorporation of multi-state models of morbidity and mortality. Mortality profiles alone will not elucidate the underlying selective pressures causing death in the Larson Site.

**Sex specific mortality**

Analysis of the adult sex-specific mortality profile lays the ground work to examine the paleopathological underpinnings associated with hypotheses as to why the Larson males and females may have a differential sex-specific risk of death. Acsadi and Nemereski (1970) found lower life expectancies and disproportionate older juvenile and young adult females skeletons in their samples and attributed this to child-bearing consequences. Similar findings have been suggested for skeletal assemblages from Medieval Europe (Weise and Boldsen, 2002),

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prehistoric Illinois (Wilson and Steadman, 2008), and protohistoric Upper Great Plains (Owsley and Bass 1979). Otherwise, reports of differential mortality between sexes have been inconsistent in the literature. A lower survivorship and higher risk of death trend is visible throughout all datasets, but overall this research does not support a sex-specific mortality pattern.

The Siler survival curves indicate a lower survivorship and thus a higher risk of death for young adults with females having a slightly higher risk in the 15 to 25 age group. Females maintained a higher risk of death than males until later adulthood. Owsley and Bass (1979) noted sex differences in the distribution of deaths through life table calculations. Owsley and Bradtmiller (1983) argue that the high number of neonatal deaths combined with the larger number of young females support complications from pregnancy as a cause of death for the Larson Arikara females and the differential in the sex-specific mortality. Furthermore, their survey of the field notes found one female in the Larson Site that had a fetus within the pelvic cavity (Owsley and Bradtmiller, 1983). However, this female individual did not have any skeletal stress markers to indicate a pregnancy related death. According to Wells (1975) complications of pregnancy were uncommon among the Arikara. This research confirms the high number of fetal and neonatal individuals and was the impetus for incorporating conception corrected age-at-death estimates into the mortality models. Even though a consistent pattern of multiple burials that contained infants with female skeletons exists (Bass and Rucker, 1976), no pathological link can be made to support the pregnancy hypothesis for the sex differential.

Upon further inspection, the confidence intervals for the male and female survival curves overlap significantly. Also, the mean age-at-deaths for males and females are not significantly different. The change in the mortality pattern for old adults could be obscuring significance of
the earlier pattern, but in the comparison of models, the Gompertz-Makeham model was not the best fitting model. An age-independent component is not an underlying cause for an increase in mortality for young adult females. Also, pregnancy as a risk factor cannot be separated from age. Clinical literature has established that the risk of pregnancy-related complications increases with age. The combination of pregnancy and an increase in infectious disease would be more realistic. Pregnancy is physiologically taxing on the body, which could make a female more susceptible to infection. However, the current evidence does not support a sex-specific adult mortality bias.
CHAPTER 8
Conclusions and Future Considerations

Conclusions
As Wood et al. (2002b) state, parametric hazard models are only as good as the model used to estimate the age-at-death distribution. The introduction of age-at-death methods that do not have the inherent reference sample biases and that conform to the Rostock protocols have enabled researchers to start examining other variables affecting mortality without having to focus on the appropriate age-at-death estimation method. This research has demonstrated that Transition Analysis is a viable option for estimated adult ages in paleodemography and provides many advantages over traditional approaches. Also, it may not be appropriate to substitute long bone skeletal ages for missing dental ages for juvenile individuals, especially for Native American skeletal material. Dental ages are more evolutionarily stable and are not as susceptible to external pressures as skeletal development. The methodological advances in dental age-at-death estimations (e.g., Shackelford et al., 2012) encourage the use of teeth and support it as the preferred method for paleodemography.

The examination of the mortality profile of the Larson Site demonstrates the utility of the Siler model as a parsimonious parametric model for understanding the demography of a past population. Even though the Siler model captured both the juvenile and adult mortality patterns, the high number of juveniles relative to adults caused the juvenile pattern to dominate the model. This would suggest that the living population comprised of mostly individuals under age eight and an even dispersal of older adolescents and adults. The results indicate a population that has high juvenile mortality, decreased adolescent and young adult mortality, and increasing
mortality with advanced age. The flatness of the survivor and hazard curves and reduced adult individuals, as indicated in the probability density function curves, raise questions as to the cemetery population’s etiology. The mortality pattern compares well with what is expected for pre-industrial populations, but has a fairly even dispersal of individuals across age categories for individuals 10 years and above. The Larson Site may represent a non-attribitional regime, but more research needs to be conducted prior to making any conclusions.

As hypothesized, analysis of the adult mortality did not find any significant differences in the sex-specific mortality. Differences in the adult mean age-at-death for males and females is negligible. However, a trend exists that could be affecting significance of the model. Females have a higher mortality in early adulthood and a lower mortality in late adulthood.

I believe there is also an underlying heterogeneity in risk of death, which is outside the scope of this research and needs to be explored further. Investigations into heterogeneity require examination of the pathology and assessing health within the population in conjunction with the demographic patterns, which still needs to be completed. I suggest a complex of bio-cultural changes associated with the disintegration of the socio-political scheme, the increased competition for resources with other Native American tribes, and the growing daily interactions with Europeans, rather than just the 1780-1781 smallpox epidemic, as the cause for the divergence of the demographic pattern from expected norms.

**Future considerations**

A few key issues were not addressed in this research, including heterogeneity in the risk of death and non-stationarity. We cannot fully understand age-specific fertility and mortality
levels from skeletal samples without accounting for survivorship, selective mortality, and the resulting age structure of cemetery samples.

Future research will more fully examine the possible sex differential in adult mortality in the Larson village. DeWitte (2009, 2010) outlines a promising model that makes sex a covariate in the model without having to reduce the sample size since males and females can be examined as one group. The adult pattern of mortality needs more investigation in terms of both the sex-specific risks and the underlying heterogeneity in risk associated with frailty.

In order to more appropriately integrate the juvenile component, relative estimates of growth should be incorporated into the hazard models following (Frankenberg and Konigsberg, 2006). Milner et al. (2008) suggests integrating growth into the models to account for changes in survivor curves. For example, positive growth rates equal elevated survival curves compared to stationary or declining populations. By assuming a stable population instead of a stationary population will allow the integration of a positive or negative growth rate. A stable population is expected to have fluctuations in mortality and fertility rates, but not drastic or rapid changes as would be seen in a catastrophic regime. As long as the population has a relatively attritional regime, population growth and decline can be integrated rather easily into mortality models.

This study opted for a parametric analysis for this study. Future work will look at other parametric approaches, like cox proportional hazard models, to evaluate risk of death associated with specific osseous ‘stress’ markers. As Milner et al. (2000) demonstrated, the individuals within a population will never have the same age specific risks. Usher’s (2000) model that incorporates age specific risks using a Weibull model with covariates can improve interpretability of the estimated parameters. It is important to understand both the demographic
profile as well as the underlying causes affecting a cemetery population, since death is an “absorbing state” (Gage and Dewitte 2009, p. 649). The Siler model performed well and has shown that mortality profiles of horticultural societies conform to a generalized human pattern (Gage, 1988), but it assumes homogeneity in risk of death even though variation in risk factors between populations adversely affect interpretations (Gage, 1989).

Current methods in bioarchaeology still treat skeletal lesions and mortality profiles as separate entities. Owsley and colleagues have focused heavily on lesion frequency to argue for the declining health of Arikara resulting from the increased contact with Europeans in the American Plains, but no published literature has incorporated the mortality profile and skeletal lesions in one model. This research provided the first step in this process by providing accurate age-at-death estimations. Accurate age-at-death techniques are vital to measuring a population’s well-being. Several researchers have demonstrated the promise in being able to incorporate multiple lines of evidence in order to address well-being of a population (Usher, 2000; Boldsen, 2007, 2008; Dewitte and Wood, 2008; DeWitte 2009; Wilson, 2010, Redfern and DeWitte, 2011). It is not until we appropriately incorporate factors, like selective mortality into a statistical model that, we will be able to address the issues raised by in the osteological paradox (Wood et al. 2008).

Furthermore, the mortality of the Larson Village needs to be compared to similar sites both spatially and temporally to better understand patterning of health and mortality from a broader epidemiological and paleodemographic context. Understanding the variations in a broader context permits a better understanding of the complex bio-cultural phenomena causing the mortality pattern in the Larson Village. Similar questions of bio-cultural responses to
European contact exist regardless of group or location, amount, rate of population loss, or degree of the regional cultural changes. The methodological and theoretical advances in paleodemography over the last several years provides the opportunity to truly explore these aspects of population dynamics.
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Appendix 1: Age distributions for the Owsley, Multifactorial/Dental (MD), Multifactorial/Skeletal (MB), Transition/Dental (TD), and Transition/Skeletal (TB) datasets.
VITA

Rebecca J. Taylor was born Rebecca J. Wilson, September 19, 1979, to Thomas and Joyce Wilson of Atco, New Jersey as the last of eight children. She graduated from Edgewood Regional High School in 1997, received a Bachelor of Science in Biology and Anthropology from Juniata College in 2001, and received a Masters of Arts in Anthropology from The University of Tennessee in 2006. She has worked with the Department of Anthropology as a graduate research and teaching assistant, the Knox County Medical Examiner’s Office as a forensic technician, and with the Disaster Mortuary Operations Response Team (WMD) as a forensic anthropologist during her time in Tennessee. She spent the last several years working full-time as the Assistant Coordinator with the Forensic Anthropology Center at the University of Tennessee and as an instructor of Anatomy and Physiology at South College of Tennessee. Currently, she is employed as a Forensic Anthropologist with the Joint POW-MIA Accounting Command-Central Identification Laboratory Hawaii.