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Chapter 12

Stable Isotopes and Selective Forces: Examples in Biocultural and Environmental Anthropology

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a Introduction

Although the biocultural paradigm emerged about a decade prior to the first anthropological use of stable isotopic analysis in the late 1970s, the paradigm and the methodology have developed in parallel and have resulted in equally prominent approaches to anthropological research. The biocultural paradigm is the main interpretive lens for understanding relationships among culture, biology and environment, and isotopic analysis is one of the few methodologies that can inform all three aspects of those relationships. Since the earliest use of stable isotopes for tracking the rise and spread of agriculture in North America in the 1970s (Vogel and van der Merwe1977), the reconstruction of plant domestication, and dietary and subsistence behaviors still dominate isotopic research, not only because the most obvious applications of isotopic analysis are food-related but also because food is a major selective force in human evolution. Diet, however, is only one of three main forces of selection, the others being disease and physical environment. Human behaviour and culture interacts with, and adds synergy to, each of these forces, and they all produce biological stress to which humans must adapt via both individual- and population-level survival and reproduction.

Assuming that stress is any physiological disruption resulting from any insult (Goodman & Leatherman, 1998: 177), the life histories of disease and physiological stress, geographic relocations and changes in food and water consumption recorded in the chemistry of our body’s tissues can simultaneously reflect the nature of, and biocultural response to, physical environments that are both abiotic (e.g., temperature, rainfall, aridity) and biotic (plant and animal communities). Our biochemical responses should also indirectly reflect landscape change, possibly even the creation of built landscapes, e.g., concentrated urban dwelling. Integrated records enable better understandings of our adaptive history and capacity in relation to the synergy among changes in diet and environment, and the evolution of pathogens and the spread of disease. Isotopic methodology and the biocultural interpretive paradigm have been around long enough now that available data are approaching the critical mass necessary for moving inference of selective forces and evolutionary processes to a higher level.

The goal of this chapter is to encourage the development of a new phase in the combined use of stable isotopic methodology and biocultural thinking, one in which both existing and newly built datasets are used to provide evidence for the operation of selective forces. Interest in these forces is found throughout scholarship in bioarchaeology and paleopathology, particularly in studies of diet, disease and epidemiologic transitions pioneered by Armelagos (1969; Barrett et al., 1998). Epidemiology is the study of patterns of disease (morbidity) and death (mortality) by age and sex related to fertility and life expectancy. The fundamental epidemiological and demographic shifts that human societies have experienced throughout time are as follows. The 'First Epidemiologic Transition' is associated with the 'Agricultural and Neolithic Revolution'. The rise of agricultural intensification resulted in increased morbidity or illness due to more impoverished crop plant diets, increased population density and the consequent spread of infectious disease. The close contact of humans with animals during their domestication also resulted in diseases such as tuberculosis (Armelagos & Cohen 1984, Larsen 2006). The 'Second Epidemiologic Transition' or the 'Age of Receding Pandemics' is associated with industrialization. In this transition, 19th century public health initiatives, combined with germ theory, among other causes, led to decreased mortality from childhood infectious diseases, increased life expectancy (30-50 years), and the resultant rise of degenerative disease as people began to live longer ~~higher~~ (Omran 1971, McKeown 2009). The "Third Epidemiologic Transition" or "the Age of Degenerative and Man-Made Diseases" characterizes the experience of today`s world. Life expectancy is further increased to over 50 years and fertility is increased, which has led to exponential population increase (see Zuckerman, this volume; Mielke, this volume). This population profile has led to the following epidemiological characteristics. Degenerative and metabolic diseases associated with overeating or diets that are high in calories but micro- and macro-nutrient poor continue to rise (see Leatherman et al. this volume)--and include obesity, cardiovascular disease, and diabetes. Neoplastic diseases, or cancers, also continue to rise as a result of long life spans and many of these are anthropogenic i.e., created by pollutants in food, air, water, soil. The evolution of antibiotic-resistant pathogens has caused the re-emergence of some bacterial infectious diseases, such as tuberculosis. Since the 1980s these factors, combined with increased globalization have produced the rise and global spread of new infectious diseases, especially viral diseases, such as severe acute respiratory syndrome (SARS), Ebola, human immunodeficiency virus (HIV), and H5N1 avian influenza (i.e. 'bird flu') (Omran 1971, Barrett et al. 1998, Esche et al. 2010; see Barrett this volume).

Emphasis is placed here on the southern Egyptian/northern Sudanese region of the Nile Valley, a region that has been fundamental to bioarchaeological research since Armelagos began to work there as a graduate student (Armelagos 1965)(some examples in this chapter come from other, less intensively studied regions and students of his students). Known as ancient Nubia, it is still one of the most intensively researched regions in bioarchaeology (see Baker, this volume; Sandberg and Van Gerven, this volume; Turner and Klaus, this volume). Armelagos documented their health through three 3 major cultural changes: (1) the Meroitic period (AD 0-130), during which the Wadi Halfa region was controlled and used by the Kingdom of Mero¨e (also known as Kush) as an agricultural hinterland with the help of the newly developed waterwheel technology, (2) the X-Group period (AD 350-550), which represents the rise of politically autonomous units following the fall of Mero˚e, and a drop in the level of the Nile, and (3) the Christian period (AD 550-1400), during which there were a series of phases (Early, Classic, Late) that reflect varying political, economic and environmental stability. Although Egypt was conquered by Arabia and brought under Islamic rule during this time, Nubia retained the Christian faith, and experienced a general increase in population growth and trade.

Armelagos and his students found that the Wadi Halfans not only suffered from conditions characteristic of the First Epidemiological Transition (nutritional diseases [iron deficiency, osteoporosis], dental disease, and infectious diseases [mainly parasitic]), but also from common modern non-infectious, degenerative and human-made conditions (e.g., arthritis, neoplasms) that characterize the Second and Third Epidemiological Transition (Armelagos 1969, Campbell Hibbs et al. 2011). In many ways, therefore, the ancient Wadi Halfans have much to teach us about adaptation.

Food availability is determined by environment (e.g., coastal/interior, tropical/temperate, climate, altitude, seasonality, soil quality, landscape) and technological capability to overcome constraints (e.g., agriculture, irrigation, storage, processing, fertilization, trade). Diet is further patterned by biology (age, sex), social complexity, belief systems, and the ability of culture to buffer biological needs from environmental stresses. The physiological response to diet is nutrition, which plays a major role in health status, from specific deficiencies in vitamins, minerals or macronutrients to over-consumption, each of which affects susceptibility to disease. Food choices/preparation (e.g., parasite-bearing foods, such as fish, or improper cooking) and seasonality (e.g., influenzas, temporary food shortage) are related to the patterning of infectious disease. Disease patterning is also a function of population density, sanitation, and geographic mobility. These factors play important roles in all of the epidemiological transitions.

a **Background**

b ***Isotopic Analysis***

c *The Tissue Clock*

The human remains excavated and analysed from Wadi Halfa, Sudan still constitute one of the largest and best-preserved skeletal samples in the world (see Baker, this volume; Sandberg and Van Gerven, this volume). Natural mummification of soft tissues due to the aridity of this region enabled diagnostic capability for pathological conditions approaching that of modern clinical medicine. Thus mummy studies were moved to a new analytical level, which included thinking in terms of populations (i.e., the population approach; see Grauer, this volume), rather than of individuals or small groups of individuals. The scale of this perspective is imperative for epidemiological research, and for integrating paleopathology into epidemiology, a field of scholarship known as paleoepidemiology (see Zuckerman and Harper, this volume). This endeavour can only be conducted with validity on large populations.

Preservation of multiple tissues also enabled use of the tissue clock i.e., the record of biological life history found in the tissues of our bodies. The isotopic compositions of body tissues reflect those of food and water consumed during tissue formation. Hence, they provide direct evidence of our environmental experiences. Isotopic compositions are measured using a mass spectrometer and expressed as δ-values in *per mil* (‰) units relative to internationally standard reference materials (e.g., for carbon, originally a fossil carbonate, and now Vienna Pee Dee Belemnite [VPDB]; for nitrogen, atmospheric nitrogen [AIR], and for oxygen, Vienna Standard Mean Ocean Water [VSMOW]). Because each tissue takes a different length of time to form and/or replace itself, the body contains a record of environmental experiences at different times during life. The Wadi Halfa sample enabled the earliest bioarchaeological dietary life history approach to disease and diet (White 1991). The life history approach now involves reconstruction of many other individual experiences across the life span including geographic relocation, disease and cultural activity. This approach is similar to what might be expected for a full forensic analysis but when taken to a population level, it can provide much greater paleoepidemiological detail.

The slowest tissue turnover rate occurs in adult bone, which represents a homogenized record of the last 15 to 25 years of life. Short-term environmental change is recorded in soft tissues, such as skin (2 weeks) and muscle (1 month), as well as in incrementally growing tissues, such as hair, nail, and dental tissues(enamel, dentine, and cementum). These tissues can represent long and permanent unbroken sequences of different formation periods (daily, weekly, annually) for up to 2 years or more before death except in cases of functional wear where part of the record is lost, and for worn or damaged dentine, which is capable of remodelling under stress. Isotopic compositions reflect a variety of environmental conditions, as discussed below, that can combine isotopic life histories of diet and residence with disease experience. This record now allows us to not only reconstruct aspects of changing biocultural behavior, but also to identify possible epidemiological risk factors. For example, age and gender are common risk factors for many nutritional and infectious diseases, especially those in infants and females of childbearing age. Risk factors may also include short- or long-term changes in diet or climate, such as seasonal food availability and climate fluctuations, versus longer periods of extreme aridity or rainfall that can affect food production and/or produce physical stress. Both individual relocations and large-scale movement of people can not only spread infectious disease but also increase susceptibility to it. Furthermore, risk factors may be altered both positively and negatively by culturally determined behaviors such as food choice and cuisine, medical systems, climatic buffering technology and behavior, and landscape alteration. Therefore, a biocultural approach is the most comprehensive one for understanding paleoepidemiological risk factors and the patterning of disease.

c *Carbon and Nitrogen Isotopes in Paleodiet and Paleoenvironmental Research*

Dietary interpretations from carbon and nitrogen isotopic data are primarily based on differences among photosynthetic plant types and position in the food chain, also known as trophic level. The two main photosynthetic pathways used by terrestrial plants are C_3 (Calvin-Benson) and C_4 (Hatch-Slack). These are distinguished by how much they exclude atmospheric ^{13}C during photosynthesis. C_3 plants, which exclude the most--and therefore incorporate the least ^{13}C--are by far the most common worldwide and include most grains, all trees, shrubs, fruits and vegetables. Plants using the C_4 pathway, and showing less net discrimination against ^{13}C, are heat-adapted. The domesticates of these are mainly tropical grasses, such as maize, millet, sorghum and sugarcane. Both pathways are used in a third plant type, characterized by Crassulacean Acid Metabolism (CAM). These plants consist of succulents and cacti, which are rarely of dietary significance.

While carbon isotopic compositions are most commonly used for reconstructing plant consumption, they can also indicate both long- and short-term environmental change because plant photosynthetic types(C_3, C_4, CAM)are adapted to different kinds of environments such as heat, photoperiod, altitude, and latitude, and will therefore vary in abundance accordingly (Tieszen 1991). Global environmental change, specifically the wide-scale burning of fossil fuels has added large amounts of ^{12}C-rich carbon dioxide to the atmosphere since the Industrial Revolution and created a systematic change in the carbon isotopic compositions of plants. Consequently, post-industrial vegetation is depleted of ^{13}C by 1.5 ‰ relative to plants that grew for most of the time humans have occupied Earth. Modern C_3 plants have a mean carbon isotopic composition of −26.5 ‰, which is distinct from that of C_4 plants (−11 ‰). This difference has enabled reconstruction of the domestication and spread of C_4 agricultural plants, such as maize, millet, and sorghum (e.g., van der Merwe 1978, Schwarcz et al. 1985).

With the shift away from hunting and gathering to agriculture, animal meat sources decreased. Dietary protein sources and trophic level are generally reconstructed using the nitrogen-isotope composition (δ^{15}N) of protein-bearing tissues. Nitrogen-fixing plants, such as legumes and blue-green algae, have δ^{15}N values close to 0 ‰ but other terrestrial and marine plants have δ^{15}N values ranging from 2 to 6 ‰. With each level in the food chain, δ^{15}N values increase by 3 to 5 ‰. For terrestrial food webs, carnivores have the highest nitrogen-isotope compositions, but even higher δ^{15}N values can occur in marine and aquatic webs because they not only have more trophic levels but they also have a higher δ^{15}N baseline (except for nitrogen-fixing, blue-green algae-based reef systems).

The global effects of the Neolithic Transition/Agricultural Revolution on the main measures of health (fertility, fecundity, morbidity, mortality) were first seriously considered by Armelagos and Cohen (1984) in the landmark work *Paleopathology at the Origins of Agriculture*. They challenged the popular idea that agriculture improved the quality of human life. Examining changes in population health all over the world, authors contributing to the volume found that the greater assurance of food supply created by agriculture resulted in greater fecundity and fertility, which resulted in population increase and density. This First Epidemiological Transition, however, was also marked by a reduction in health quality as the shift from the more varied diet of the hunter-gatherer to dependence on cereal monocrops, combined with ecological change resulting from landscape modification and greater population density, resulted in greater morbidity and mortality, especially from acute infectious and parasitic conditions.

This volume set the stage for isotopists and paleopathologists to take the examination of the First Epidemiologic Transition to the next analytical level. They did so by testing the hypothesis that diet was associated with skeletal diseases such as iron deficiency and osteopenia, which is lower than normal peak bone density. Both of these conditions can have several different causes such as parasites or multiple childbirths respectively (e.g., Turner & Armelagos 2012, White 1986, White & Armelagos 1997, White et al. 2004, 2006, Wright & White 1996). To date, however, little has been done to broaden the use of isotopic analyses to investigate the spread of infectious disease or reconstruct relationships between the physical environment, geographic mobility, and disease.

a **Case Study: Isotopes and Epidemiological Risk Factors/Synergies at Wadi Halfa and Surrounding Regions**

Knowledge of epidemiological risk factors can be used to identify the potential of evolutionary forces to operate on populations or segments thereof, such as gender, age, and socio-economic status. Isotopic studies of change in diet and environment related to seasonality and/or mobility, and their synergies with pathology, can further enable the detection of evolutionary forces and help us to understand our biological and cultural capacities for adapting to stress under different conditions. Long-term studies can demonstrate the ability of culture to either buffer or exacerbate the stress of these forces on populations.

The Wadi Halfa Nubians offer examples of all of the above. A significant failure of cultural buffering in this region was human-induced environmental/landscape change. The powerful Meroitic Kingdom (AD 0-130) centered further south introduced widespread irrigation agriculture to the Wadi Halfa area in order to turn it into an agricultural hinterland. The resulting ecological and landscape change produced the unintended consequence of endemic (regularly occurring and persistent versus epidemic) shistosomiasis (Miller et al. 1992). Schistosomiasis is a parasitic disease carried by fresh water snails infected with the blood fluke parasite, Schistosoma. Even today, schistosomiasis is the one of the world’s most important water-based diseases from a global public-health perspective (WHO, 2002). With about two-thirds of the ancient Wadi Halfa adult population infected, shistosomiasis must have had a profound effect on working capacity and mortality (Campbell Hibbs et al. 2011). The epidemiological effects of water-borne parasitic and infectious diseases might be further examined using their relationship between water source, via oxygen isotope compositions (see below) and biosocial variables of status, gender, and age (e.g., Lightfoot et al. 2014).

After the fall of the Meroitic Kingdom, irrigation enabled the X-Group population to survive a period of increased aridity and a naturally occurring drop in the level of the Nile. Not surprisingly, isotopic data for this time period also indicate a significantly greater consumption of C_4 staples (millet and sorghum), which are much better adapted to arid conditions (White & Schwarcz 1994). Other important cultural buffering attempts included seasonal C_3 and C_4 crop rotation and food storage, where the heat-adapted but least nutritious C_4 foods were consumed in summer. Although food storage was commonly practiced, isotopic analysis of sequential hair segments from root to tip from Wadi Halfa mummies showed that food storage was mainly a precautionary measure against crop failure because people ate their crops mostly in the season in which they were harvested (Schwarcz & White 2004). Fruit and vegetable crops, however, would have been less available at the hottest time of the year, so the combination of nutritional and heat stress made the summer a period of high morbidity and mortality (White

1993), a situation that still exists today. Nonetheless, these populations were likely buffered from many infectious diseases by processing grain in the form of beer, which produced Streptomyces, an actinobacterium that fluoresces in bone and has antibiotic properties (Bassett et al. 1980, Nelson et al. 2010). The relative absence of infectious disease in these populations may indicate consumption of therapeutic doses (Armelagos 2000).

Isotopic data reveal that culture change, marked by the return to political and economic autonomy during the X-Group period, had both positive and negative effects on biological adaptation. Breastfeeding, which has culturally determined rules and parameters for duration and cessation or weaning, creates a trophic level isotopic effect. Because nursing infants consume only breastmilk, which is a human tissue, they are one feeding level higher than their mothers. The late beginning and long process of weaning, which occurred between 2 and 6 years of age at Wadi Halfa as indicated by δ^{15}N and δ^{18}O values throughout the temporal sequence, would have exerted protective effect against protein deficiency. However, since breastmilk is nutritionally inadequate for the dietary needs of children over approximately six months of age, such prolonged breastfeeding would have predisposed them to iron deficiency (White & Schwarcz 1994, White et al. 2004). Iron deficiency was endemic in childhood, as were high levels of early childhood growth disturbance, as indicated by dental pathology (Rudney 1983). Throughout life, isotopic data also indicate that anemic individuals consumed more C_4 foods and protein from lower trophic levels.

Nonetheless, childhood health improved during X-Group times, increasing life expectancy (Rudney 1983). Sexual dimorphism, however, which generally signals increased stress experienced by males, decreased during the X-Group period (Vagn Neilson 1970). Isotopic data indicate that although males consumed more C_3 foods and protein from higher trophic levels than females throughout the sequence, during X-Group times their C_4 food consumption equalled that of females and the trophic level of their protein dropped (White & Schwarcz 1994). Notably, the dietary pattern that characterizes both anemia and male stress is the same. A variation of this theme is found in the diets of individuals with osteopenia. These individuals were mostly female, but also males and juveniles (Martin and Armelagos 1985). Osteopenic individuals also consumed significantly more C_4 foods, but instead had higher $\delta^{15}N$ values (White & Armelagos 1997). High $\delta^{15}N$ values are not only associated with osteopenia and osteoporosis but can also be induced by starvation, pregnancy, and diseases that cause a negative nitrogen balance, such as infection from trauma or wounds, arthritis, and acquired immune deficiency syndrome

(AIDS) (White & Armelagos 1997, Fuller et al. 2004, Katzenberg & Lovell 1999, Olsen et al. 2014, Williams 2008).

Although analysing unhealthy individuals might invalidate the use of nitrogen isotopic data for some paleodiet studies (but see Olsen et al. 2014), they could be used to identify epidemiological risk factors. For example, work by Williams (2008) west of the Nile in the Dahkleh Oasis combines segmental nitrogen-isotope data from hair with the solar alignment of burials. This integrated method significantly advanced detailed information on the timing of trauma and healing, conception, and pregnancy relative to timing of death. The majority of conceptions could be traced back to a cultural fertility event, the Feast of Maat. This work vastly improves our understanding of female risk of morbidity and mortality in particular, and emphasises the role of culture in biological outcomes. The above studies are also a good reflection of how isotopic analyses can inform understandings of our chemical, morphological (e.g., body height), and physiological (e.g., length of breast feeding, nutrient requirements) adaptive domains.

One of the most important factors in the geographic spread of infectious disease is travel, which can be identified by; tracking change in the isotopic compositions of incrementally growing tissues, comparing earlier and later forming tissues, and/or comparing the tissues of individuals with known environmental baseline δ-values. The two elements whose isotopic compositions are most commonly used for reconstructing paleomobility are oxygen and strontium, although carbon and nitrogen can also be used when there are differences in ratios of C_3 to C_4 foods and/or protein source or trophic level among the regions of interest. For example, carbon and nitrogen isotopic data for humans have been used at the northern Sudanese site of Kerma to identify the presence of 'outsiders' or non-locals for the region (Thompson et al. 2008). Environmental variables such as rainfall, humidity, temperature, altitude, and distance from the ocean are reflected in the oxygen-isotope composition of meteoric water (Dansgaard 1964), which is in turn reflected in body water, and then in the phosphate ($\delta^{18}O_p$) and structural carbonate ($\delta^{18}O_{sc}$) of mineralized tissues (Longinelli 1984). Variability in $\delta^{18}O$ values of archaeological skeletal tissues can be caused by seasonality, the presence of water sources subject to different degrees of evaporation, the possible consumption of foreign foods with high water content, and some pathological conditions. For example, females from Wadi Halfa with evidence of osteopenia had the lowest $\delta^{18}O_p$ values, which could indicate that osteopenia was more frequent or severe in women. Alternately, it may indicate that the sample included a large number of breastfeeding females who had high water flux rates (White et al. 2004).

Geographic mobility is only detectable when involved locations and/or water sources have significant climatic and/or physiographic differences. Nile river water has graduated $\delta^{18}O$ values that reflect increasing evaporation from source to delta. It is also virtually the only water source for those living on its banks and the Nile was the main corridor for north-south travel in the region. Because of its central location, it is not surprising that Wadi Halfa had among its dead isotopically identified non-local individuals who must have been travellers (White et al. 2004). If these individuals brought infectious bacterial diseases to Wadi Halfa, they did not take hold, possibly because the consumption of antibiotics through antibiotic-laced beer was widespread and conferred immunity. Disease could have also travelled east to west via the caravan travel and trade routes between Nilotic settlements and the Western Desert oases. For instance, at the Dahkleh Oasis, which draws its water from a fossil aquifer with a distinctive $\delta^{18}O$ value, the discovery of a male with skeletal evidence of leprosy and a Nile Valley isotopic composition has led to the suggestion that oases may have been used as places of exile for such diseased individuals (Dupras & Schwarcz 2001).

Radioactive decay, geological age and compositional variability among rocks, minerals and seawater lie at the root of strontium-isotope variations used as tracers in anthropological studies of geographic mobility. As one of the isotopes of rubidium (^{87}Rb) decays, ^{87}Sr is formed. Higher ^{87}Sr/^{86}Sr ratios occur in rocks and minerals that are richer in Rb, which follows K, and/or which are older, thus allowing more time for decay of ^{87}Rb to ^{87}Sr. Rocks and minerals that are poorer in K, and hence Rb, and/or geologically younger have lower ^{87}Sr/^{86}Sr ratios (Faure & Powell 1972). Strontium-isotope ratios are, therefore, a function of the age and type of rock. Seawater also has a characteristic ^{87}Sr/^{86}Sr ratio at any given time. This ratio has, however, varied throughout geological time depending on the age and sources of strontium delivered to the oceans. Strontium isotope ratios are typically measured using thermal ionization mass spectrometry (TIMS) or laser ablation-multi collector-inductively coupled plasma-mass spectrometry (LA-MC-ICP-MS).

Over time, rock breaks down into soil, and strontium moves into soil water and then through the food chain without significant alteration of its isotopic composition (e.g., Comar et al. 1957). Variation can be created by local factors, but the strontium-isotope compositions of diets directly reflect local geology, and almost all strontium in the body is found in mineralized tissue. The strontium-isotope composition of seawater is similarly transferred to calcium-bearing tissues in marine organisms. Both strontium- and oxygen-isotope analyses have pushed back the biological evidence for long distance interaction between Egypt and Nubia to the New Kingdom period (~1050–1400 BC) (Buzon et al. 2007, Buzon & Bowen 2010, Buzon & Simonetti 2013). The next step in paleomobility studies would be to correlate the presence and incidence of infectious disease with isotopically identified individual travellers and immigrants, and its spread in past populations.

b ***Isotopes and Paleoenvironments***

Traditional approaches to isotopic reconstruction of paleoenvironments include the use of incrementally deposited materials. For long-term records, these include lake and marine cores, ice cores, speleothems, which are mineral deposits formed from groundwater within underground caverns, and tree rings. Incrementally formed animal tissues, such as otoliths, or inner ear bones, shell, horn, antler, teeth, and hair provide shorter records of change. These records can only be extended across long periods of time when samples that can be correlated with each other are available. Unfortunately, many chronologies of climate and ecological change created in this way either predate human occupations of the regions involved (e.g., Brook et al. 2010, Nicoll 2001, Osborne et al. 2008, Stanley et al. 2003)or are unavailable for many regions. In other cases, these chronologies have not been linked to human experiences except to identify associations between climate change and the fall of civilizations (e.g., Issar & Zohar 2004, Weiss 1997). Environmental and ecosystem change, when integrated with dietary and disease patterns could, nonetheless, demonstrate presence of selective pressures.

The use of human remains for the strict purpose of environmental reconstruction is largely unexplored, and would likely be frowned upon for ethical reasons in many places. We do not advocate the analytical destruction of human tissues for the sole purpose of environmental reconstruction. We would, however, like to alert researchers to the possibility that there may be inherent climate or environmental records in samples of human remains that have been previously analysed for both diet and mobility ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$). Where human remains are not available because of politics or preservation, the remains of both wild and domesticated animals often make good proxies for reconstructing not only food domestication and the rise of agriculture and pastoralism, but also cultural and economic change, social organization, and ideology (e.g., Szpak et al. 2014a). Isotopic data for animals can provide additional evidence of landscape change as it is related to climate change and/or human subsistence behavior and population growth and decline (e.g., Morris 2015). As more and larger sets of human and animal data are produced to investigate anthropological and ecological issues and questions, there is increasing potential to mine the environmental and landscape information that they contain.

The nitrogen isotopic composition of plants reflects rainfall and aridity; as rainfall decreases, δ^{15}N values of plant and animal tissues tend to increase. It can also reflect altered soil quality caused by nutrient loss or fertilization. Nutrient loss related to environmental degradation and ecological change could be signaled by a gradual reduction of δ^{15}N values as environments reach their carrying capacity and populations are forced to consume protein from lower trophic levels. Fertilization in agriculture can be artificial or be the result of natural processes, such as the annual deposition of nitrogen-rich silt during annual flooding of large rivers like the Nile (e.g., Jenny 1962). The δ^{15}N values of bone collagen also indicate that such an occurrence happened over time at Wadi Halfa (White and Schwarcz 1994). In this case, the fertility of the Lower Nile came at the expense of the Upper Nile. Fertilizing soil is also a human behavior that, in ancient times, was most likely to be organic via dungs, slurries, fish, seaweeds, and guano, and produced plants with higher δ^{15}N values. Whether fertilization is a process of nature or a purposeful human act, it induces environmental change. Although first seen as a source of error in paleodietary research, fertilization systematics are now being used to reconstruct the rise of intensive agriculture and its link to animal domestication, husbandry practices (e.g., complete captivity, controlled herds, and pasturing locales), and land use patterns (Balasse 2014, Hamilton & Thomas 2012, Makarewicz & Tuross 2012, Szpak 2014b). The next steps could be to tease out the environmental change associated with human behaviour, and reconstruct the relationship between animal husbandry and domestication practices and the rise of zoonoses, diseases with animal origins that infect humans (e.g., Barton et al., 2009, Donoghue 2011).

Paleotemperature can be reconstructed from the oxygen isotopic composition of non-mammalian animal proxies. For example, growth rings in the shells of mollusk species directly reflect the temperature of surrounding water bodies during shell formation. Because humans and all other mammalian species have a tightly regulated, consistent body temperature, the isotopic composition of the ambient air temperature will not be recorded directly in mineralized tissues. Rather, these tissues will reflect environmental effects on the oxygen and hydrogen isotopic composition of the water consumed. For example, seasonal shifting in $\delta^{18}O$ values related to fluctuating levels of the Nile has been reported in a preliminary study of variation within human osteons, the main structural unit of bone (Schwarcz et al. 2004). By long-term extension, when bulk bone $\delta^{18}O$ values from Wadi Halfa humans are combined with those from other studies, a record of the average Nile environment can be reconstructed from Predynastic (6950 to 4950 BC) to modern times (Iacumin et al. 1996, Geirnaert & Laeven 1992, White et al. 2004). This record indicates a long period of increased aridity that began around 1500 years BC (Jackson 1957, Geirnaert & Laeven 1992) as well as climatic variability in source regions (Bell 1970, Butzer & Hausen 1968, Pollard 1968) and more recently, the evaporative effects of the Aswan dam.

a **Discussion and Conclusion**

The explanatory power of stable isotope analysis combined with the biocultural paradigm holds much promise for future understanding of how the evolutionary forces of diet, disease and physical environment have operated on humans throughout space and time. In addition to serving the goals of paleopathologists to reconstruct pathogenesis and epidemiology, understand histories of diseases, and inform medical knowledge, theory and practice, such integrated lines of evidence also inform paleoenvironmental research. This approach would improve our understanding of the impact of climate and environmental change on populations and their biological and cultural adaptive capacity. The aggregate information derived from all of these efforts should ultimately be funnelled into a biocultural model that can benefit modern quality of life and biological well-being.

As the work of Armelagos with the Nubians at Wadi Halfa has taught us, the biocultural approach in bioarchaeology provides data that enable us to better understand stressors and their effect on ancient populations. Stress can be caused by any evolutionary force, and inferred from isotopic data that directly indicate short- or long-term change in diet and climate, or indirectly indicate susceptibility to disease experiences. Our main buffer against these stresses is culture but culture, particularly its technological aspects, can also create stress on an enormous scale. This dynamic is evident: in the changing dietary and health profile of Wadi Halfans during the Agricultural Revolution and the associated First Epidemiologic Transition, in the changing disease and demographic patterns of the other epidemiological transitions, and in the modern concern for human-made climate change, pollution and landscape alteration.

Ultimately, the goal of the biocultural isotopic anthropologist should be to integrate isotopic data on geographic mobility and diet with changes in the physical and cultural environments, and in patterns of disease and demography. Such integration would make epidemiological risk factors more clearly detectable. More specific knowledge of the dynamics of those risk factors and their biocultural outcomes in ancient populations should inform the way we handle similar modern situations. Currently developing methodological approaches in isotopic research will further the quality and specificity of our reconstructions. These include; 1) expanding ways of using the tissue clocks, which will involve new ways of micro-sampling and help to minimize sample destruction, 2) expanding knowledge and application of other isotopic systematics, such as sulphur, hydrogen and iron and 3) combining multi-element isotopic data to hone our ability to identify food consumption and geographic relocations, 4) further developing the use of amino acid isotopic analysis to distinguish between influences of diet versus metabolic, physiological, and disease stresses on isotopic composition.

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