Anthropological Energetics 2017: A Proposal

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Abstract: In the twenty-first century, energy in all its manifestations became the issue of the day. As new insights about Earth's geo-history emerged, so did worldwide concern about human consumption of fossil energy as a force in global climate change. These insights and concerns added another dimension to anthropological examinations of how energy and energetics have affected human biological evolution and how they impact cultural developments. It is time to consider how our discipline can integrate these understandings into our anthropological worldview and practice. This paper reviews these topics and argues for an active anthropological role in shaping public perspectives on the history of *Homo sapiens* and the responsibilities of our species in the years ahead.

Descriptive key words: anthropological worldview, energetic trade-offs, thermodynamics, Earth history, climate change

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In the second decade of the twenty-first century, energy became the issue of the day. To respond to worldwide concern about global climate change, attributable in part to fossil fuels releasing gases such as carbon dioxide, methane, and nitrous oxide into the atmosphere, disciplines such as physics, chemistry, geology, and biology provided increasingly precise explanations of Earth's climate systems. These included data on the origin and development of life on this planet. More clearly than ever, people are seeing connections among energy, Earth's inanimate materials, and its living forms. When viewed together, the insights achieved in separate fields constitute nothing less than an intellectual revolution equal in scope to all others in recorded history.

Energy and energetics, the analysis of energy's transformations, can be incorporated into anthropology's traditional themes of evolution and bio-cultural adaptation to diverse environments. We have used energetics to explain the evolution of specific features of human biology, and have applied energetics to understand resource variation as people adapt customs to specific environments. Now it is time to integrate new understandings of the central role of energetics into our anthropological worldview, both in teaching and research.

Andrew Knoll (2003, p. 224) wrote: "Life and environment evolved together, each influencing the other in building the biosphere we inhabit today." Within this biosphere, humans originated, adapted, and now dominate, for the good or ill of the planet and our species. In this paper, I review key episodes in Earth's history and then address energetics as central to biological and cultural evolution. The subject is staggeringly comprehensive, so its presentation in this article must be introductory and suggestive. The first section, which concerns Earth as our planet, portrays the setting for life that too often is taken for granted by biologists and anthropologists. Life arose from materials provided on the early Earth, and, simply by living, microbes transformed the planet and produced a protective atmosphere. The second portion features examples of energetics in biological and cultural evolution.

EARTH AS OUR PLANET

About 4.6 billion years ago, Earth emerged as a swirling ball of mass and energy. Earth's interior was intensely hot and its exterior shell held thick mounds, or masses, of solids and liquids. The sun emitted only about three-quarters of the energy it does now, and its surface was roiled with giant eruptions that spewed enormous amounts of material and radiation into space. Meanwhile, our planet's surface warmed, initially helped by nitrous oxide, a greenhouse gas.

Creation stories that anthropologists have recorded in diverse cultures help us picture an almost unimaginable transformation. Some stories tell of a formless ocean with small bits of land protruding from the depths, while others describe a being such as a giant turtle rising from the water to establish land. A traditional story I learned from an elder of the Coquille Indian tribe of Oregon's south coast says a World Maker sent four sounds around the world, while a later being walked along the shore and wove a mat to make a beach. With this transformation, the tides no longer washed inland and disrupted villages, and Earth slowly was made more habitable. Many peoples have legends with two or more stages, the first for creation and the others to modify Earth for human needs.

Science can more easily report attributes the early earth did not have that now are present than it can definitively describe its features. Paramount is the lack of atmospheric oxygen – the air held as little as 0.001% compared to our current 21% atmospheric oxygen. There were no living beings – no organisms with metabolic systems that reproduced themselves (Canfield, 2014; Falkowski, 2015). What Earth possessed, however, were material ingredients and energy essential to build the world we inhabit.

Changes in the physical planet have long been central to the anthropological story of human evolution. For example, glacial episodes have helped evolutionary anthropologists understand the dispersal of humans across Eurasia. Presence of human fossils in Java would not make sense without knowledge of glaciation reducing the sea level, thus allowing ancestral humans to walk to Java almost two million years ago. Each new geologic discovery has helped explain species distributions while apparently anomalous fossils have spurred geologists to find explanations. For example, connections among fossils in southern continents supported the concepts of continental drift and plate tectonics.

From a human perspective, plate tectonics is both a great creator and a great destroyer. It cycles carbon and rock, revitalizing soils and nourishing the earth, but ash from volcanoes may block the sun, eliminating entire growing seasons, and lava can bury cities and their people. Moving continental plates create mountain ranges and plateaus that alter climates and affect plants and animals. Changing climates provide evolutionary opportunities for some life forms, even as they doom others.

Geoscientists differ on when plate tectonics began, though there appears to be general agreement that it has operated for more than three billion of the earth's 4.6 billion years. One highly mathematical theory proposed to explain the origin of the process involves differences in the temperature and weight of oceanic vs. continental crusts that led to collapse of some of Earth's first continental masses. As collapsing crusts spread outward and collided with less mobile masses, some proto-continents sank under others in a process that became self-sustaining and continues today (Hadhazy 2014; Rey, Coltice, & Flament, 2014). Whether this theory of subduction earthquakes holds up or others supplant it, plate tectonics is known to be ancient. We have come to understand that the process is crucial to the continued evolution of Earth and its life forms.

[see TABLE 1 - Geologic Time Line, p. 33-4]

LIFE WITHOUT OXYGEN – THE ARCHEAN

"Life was forged by the same physical and chemical process that shaped our planet and oceans," (Knoll, 2003, p. 72). Incredibly, the design for mobilizing energy for metabolism and reproduction evolved early in the history of life. Living things require energy and employ a transfer of electrons, or what is called an electrical gradient, to generate it; the process works essentially the same way that batteries do (Falkowski, 2015, p. 59). Access to a flow of energy was necessary to the origin of life and is required to maintain it. For metabolism, all biological machines have to produce adenosine triphosphate (ATP), which transports chemical energy within cells. Bill Mesler and James Cleaves conceive of the earliest organisms, called LUCA for Last Universal Common Ancestor, as existing together, "less like a community of organisms and more like a communal organism." They admit that their scenario, though reasonable, is hypothetical: "The reality is that nobody knows exactly what the environment was like...nor does anyone know what LUCA's internal chemistry was like" (Mesler & Cleaves, 2016, p. 224-5).

Free (atmospheric, un-bonded) oxygen was not required for the initial life process but was necessary if a microbe was to increase its size. However, free atmospheric oxygen was rare because it combines readily with other elements. In Earth's early days, oxygen may have represented 0.001 % of its current level and its increase to 21% of the atmosphere was extremely slow (Canfield, 2014).

Several hundred million years after the first microbes arose more than three billion years ago, cyanobacteria (blue-green algae) evolved. These new forms split water (H_2O), producing free oxygen (O_2). Like all living things in the first two billion-plus years of life on earth, early cyanobacteria lived in the ocean. They produced oxygen as a waste gas that readily combined with chemicals in the water until there were no more chemicals in the ocean to combine with (Porder, 2014). Entry of oxygen into the atmosphere is thought to have begun at least 2.2 to 2.4 billion years ago; though a long, slow process, it changed life forever, hence the name, The Great Oxygen Event (Table I).

Microbes remained small for a billion years, even as their numbers swelled. When atmospheric oxygen sparked the evolution of oxygen-dependent microbes, most of the early microbes died. Now the closest living descendants of early anaerobic organisms live more than 100 meters below the surface in the Black Sea (Falkowski, 2015). When oxygen entered the atmosphere, it readily combined with methane, a big component of the atmosphere.

Methane (CH_4) is one of the major greenhouse gases contributing to global warming today, but because it combines readily with oxygen it has only a 10-year life in the atmosphere. If we for the moment ignore the specter of methane hydrates that will be released from permafrost (Wadhams, 2016), we could address atmospheric methane by severe controls on landfills, natural gas wells, leaks in natural gas pipelines, and ruminant agriculture. Controlling these sources would require concerted action and enormous investments by many countries. Such wide-scale efforts sound fanciful, but that is only because conditions have not yet deteriorated to the point that world leaders are ready to consider what is at stake if we do not act.

Snowball Earth

The earth is thought to have been quite warm during most of earth history, but there were several periods when all or most of the earth's surface was frozen (Wadhams, 2016). The first episode was in the Proterozoic when the sun was weaker and methane was a major greenhouse gas (Table I). No single theory of what produced the extreme cold is fully accepted. One proposal suggests that oxygen, released by photosynthesis, combined with atmospheric methane and thereby reduced its greenhouse effect. Stephen Porder describes it like this: "Free oxygen destroyed the atmosphere's methane, the greenhouse gas that kept the planet warm. That induced the first global glaciation" (Porder, 2014, p. 30; Kump, Kasting & Crane, 2010). Wadhams (2016: 26-27) suggests that this early frozen episode of up to a billion years may have been repeated for shorter periods of time at 710 MYA at 635 MYA. In between these two latter glacial episodes, marine planktonic algae began to flourish.

OXYGEN AND CARBON DIOXIDE: PLANTS AND ANIMALS

All energy comes from the sun but free oxygen is central to transforming that energy for use on earth, and understanding this process is only centuries old. The concept of a gas that fosters combustion was known in the late seventeenth century, but it was not till 1778 that French chemist Antoine Lavoisier gave it the name oxygen and scientists grasped its significance. Scientists learned that plants emit oxygen as a by-product when they make living tissue, and in the nineteenth century applied the term photosynthesis to the process that uses water, carbon dioxide, sunlight, and chlorophyll to transform solar energy, rendering it useful on earth (Morton, 2007).

Photosynthesis lies at the core of the complementary relationship between plants and animals that is both wondrous and as obvious as dirt. The process seems simple only because we who learned about it during childhood take it for granted, but it has its own evolutionary history (Knoll, 2003, p. 86). In 2017, a theory was proposed to relate the emergence of animals to a food source, abundant marine algae in the Cryogenian (Brocks et al., 2017). Following the Cryogenian was the Ediacaran, defined by appearance of trace fossils of complex but enigmatic multicellular organisms. Discovered in the 1940s, the strange looking organisms are named for the Ediacara Hills of South Australia where they were first identified. They have since been found in many sites on other continents. Whether Ediacaran life forms continued into the Cambrian is debated among paleontologists. Some believe Ediacarans have descendants among the much more plentiful and better-known Cambrian fossils. The term Cambrian Explosion makes it seem that a group of organisms immediately took center stage in the history of life, but, like the Great Oxygen Event, development of the Cambrian assemblage of fossils took millions of years. Among Cambrian forms are body types that are common in our most familiar species, while others appear strange to us because they did not continue. The extreme diversity of Cambrian fossils suggests a sort of natural experiment, a random production of structures, some of which formed the basis of continuing families of organisms.

Following the Cambrian period, the Ordovician is known for diversification of marine life. The subsequent period, the Silurian, provides the first clear evidence of land-living organisms. Early trees and forests were identified in the next period, the Devonian. The subsequent warm, humid period was given the name Carboniferous because it holds many coal deposits. Canfield (2014) estimates that in the Carboniferous the percentage of atmospheric oxygen rose to 35%, but he recognizes that not all experts agree on an exact percentage. Giant insects at the close of the following period, the Permian, suggest atmospheric oxygen higher than our current 21% because high levels of oxygen must have been required to power fossil insects with wings that stretch to 45 cm, tip to tip. Increase in the size of animals and in the proportion of free oxygen seem to have co-occurred, but scientists differ in how to interpret this relationship. Did increases in oxygen give rise to greater diversity and size, or did increases in size of some animals lead to higher oxygen levels? (Canfield, 2014; Falkowski, Katz, Milligan, Fennel, Cramer, Aubry, Berner, Novacek, & Zapol, 2005).

The Carboniferous lasted 60 million years, during which time animals laid the first amniotic eggs. These remarkable shells protected reptilian embryos, allowing them to breathe and not dry out, an innovation necessary for reptiles living on land. Continued interactions between Earth's chemistry, atmospheric gases, and consequences of plate tectonics (vulcanism, earthquakes, mountain building, and positions of continents) created climatic challenges along with new opportunities for evolution. Each innovative life form relies on nourishment, i.e., energy, provided by prior innovations. Plants feed animals and consume CO_2; forests made possible the evolution of birds by creating a place to land and build a nest.

ENERGY AND EVOLUTION: THERMODYNAMICS

Energy conservation is important in evolution. Still, some species evolve using greater amounts than competitors but succeed because they are more efficient in obtaining food or because they produce more descendants in given amounts of time. Prior species may continue by avoiding competition either by developing different morphologies or behaviors such as food choices and activity schedules. Brian McNab's book *Extreme Measures* (2012) contrasts marsupials' reproductive physiology with that of placental mammals. Internal development of a foetus, whether marsupial or placental, requires a solution to the problem posed by the mother's immune system rejecting a foetus as if it were a foreign substance. Marsupial young have a shell membrane that lowers the risk of immunological rejection but also limits the size and development of young, which are confined to the pouch. Eutherians instead grow a placenta with a trophoblast that provides a barrier between maternal antibodies and foetal antigens. The placental solution to immunological rejection offers more nourishment and the ability to have a more mature infant at birth.

No evolutionary development comes without a cost – in this case, energy. In return for faster development, placental mammals have a higher metabolic rate. Given an environment with adequate nourishment, the placental adaptation has proven to be successful for many species in many niches (McNab, 2012).

This placental-marsupial contrast exemplifies a trade-off, a concept human biologists use in analyzing behavioral and physiological adaptations that species, individuals, and cultural groups make to survive in environments with limited resources. The trade-off concept can apply to diverse topics, the most basic concerning the two laws of thermodynamics – that energy can be transformed but not lost or gained; and that energy tends to spread and dissipate. Oliver Morton (2007, p. 90-92) wrote that life "accepts the burden of entropy [second law] in order to take the benefits of energy [first law]."

He described the trade-off concept poetically to express a profound relationship between living forms and the universe, a relationship that philosophers have mulled and argued about as they grapple with the meaning of life.

ENERGETICS IN HUMAN BIOLOGICAL EVOLUTION

Reproductive physiology

Many species have evolved reproductive cycles in which adult females become sexually receptive to males at the time of year that assures that offspring are born when maximal food is available. A female's receptive period often is advertised with scent and visual signals such as swelling of tissues. Humans differ from most primates in not advertising receptivity. Though fertile for only a few days of each month, they are sexually receptive year-round. Some primates shed blood if an estrous cycle does not lead to a pregnancy, while shedding of blood occurs monthly in humans throughout the year if fertilization and implantation do not intervene. In explaining differences in receptivity, anthropologists have linked the human pattern to long-term pair bonding, which tends to ensure that mates will cooperate to nourish offspring until maturity.

Two other questions about the human reproductive cycle beg to be answered: why is the endometrium that is prepared monthly shed, rather than maintained; and why does menstrual cycling end at a particular age? Barbara Strassmann (1996a, 1996b) investigated whether there is an energetics explanation for shedding the endometrium and building it up again each month. She used calculations of the energy cost of the monthly cycle to determine which pattern, maintaining or re-building, would use more energy. Energy costs vary during different segments of the cycle, with a high cost when the endometrium is developed and low cost immediately after it is shed. Her analysis indicated that the year-round cycling system saves approximately half a month of calories that would be spent if the endometrium were retained, a significant amount for early hominins and for humans in any society that has minimal resources.

Why, then, does a woman's cycling end? At the time of Strassmann's work, gynecologists questioned the significance of menopause and considered how to treat it medically. Some human biologists instead suggested that menopause has social or biological benefits and is not a medical condition requiring drugs or other medical attention. What evolutionary benefit could menopause provide?

To address this, I applied Strassmann's energetics-based formula. I proposed that menopause evolved as an energy savings program. Non-industrial and non-affluent communities past and present likely would benefit if older women required fewer calories than young women do, and there are further considerations. The chance of a mother living through the years that her child requires care declines the older she is at the time she gives birth, and loss of a mother can harm both the new infant and older children. Compounding the energy cost of preparing the body to receive a foetus each month is the fact that egg quality declines with age, leading to higher rates of miscarriage and congenital defects. Both entail loss of the nourishment invested in a pregnancy. In many communities, older women help to rear offspring of adult children, and diversion of efforts to their own infants would represent an additional cost (Hall, 2004).

Primatologist Jane Goodall provided an illustration of family costs that older mothers bear. Commenting on the misfortunes of Flo, an exemplary chimpanzee mother, Goodall laid out the issue years before Strassmann or I posited energetic hypotheses about human reproductive physiology. After describing the tragedy of Flo's final pregnancy, the death of the infant, and the subsequent death of Flo's son Flint who mourned for the loss of contact with his mother that her final pregnancy caused, Goodall concluded: "If she had not conceived again, all would, I think, have gone well for Flint. But that last pregnancy drained so much strength and energy from Flo's aging body that she was simply not able to wean Flint" (Goodall, 1990, p.193). Goodall believed that Flo and her son Flint would have benefitted if Flo, in effect, had experienced menopause. Similar scenarios taking place in human societies over many thousands of years may have selected for cessation of menstrual cycling that we know as menopause (Hall, 2004).

Food Choices and Preparation

Animals that primarily eat plants spend more time in the food quest than do carnivores, and require substantial digestive tracts to obtain sufficient energy. Since their origin early in the Cenozoic, primates have been omnivores, eating insects and plants, but species differ in the proportions of these food types. Leslie Aiello and Peter Wheeler (1995), concerned about how hominins got the energy to develop larger brains than other hominoids, proposed that increases in hominin brains are best understood as resulting from the energetics of eating meat. Their "expensive tissue hypothesis" integrates energetics, food choices, and brain size to explain how larger hominin brains evolved without increased metabolic demands. Adding meat to the diet, they argued, allowed a reduction in gut size and a transfer of energy from the gut to a slightly larger brain.

Studies of early Pleistocene hominin skeletons tend to confirm a reduction in the breadth of the trunk, where digestive organs lie, along with a slight enlargement of the cranium. In 2011, almost twenty years after Aiello and Wheeler published their hypothesis, support for the hypothesis came from identification of genetic changes in glucose transporters that are traced to that same era (Fedrigo, Pfefferle, Babbitt, Haygood, Wall, & Way, 2011; Harris, 2015).

Although Aiello and Wheeler did not discuss cooking in detail, they noted (1995, p. 210) "Cooking is a technological way of externalizing part of the digestive process." This statement foreshadowed a second set of hypotheses about energetics and food, developed by primatologist

Richard Wrangham and colleagues. Wrangham posited that, like other dietary changes, cooking food has had major biological and behavioral effects and, in effect, turned hominins into humans (Wrangham, 2009). The central concept is that cooked food offers more energy than raw food. Just as during the twentieth century Glyn Isaac described stone tools as crucial to hominin development by opening up the package – cutting through the hide covering the meat, or cracking open the bone that hides marrow inside – so cooking makes additional animal and plant foods, and more calories, available to humans. Stone tools plus cooking selected for smaller teeth as well as a smaller gut, in this hypothesis.

In an interview with Kate Wong in a *Scientific American* issue on food, Wrangham discussed his hypothesis (Wong, 2013). He combined his interest in when hominins began to use fire with an interest in diet. Observing chimps eating, he sampled their food and found it unappetizing, dry, fibrous, and unsatisfying. Finding no nutritional analyses of raw chimp food to compare to cooked human foods, he launched his own investigation. Research into food values led to other lines of inquiry, including unique aspects of human social behavior.

Though less interested in cooked meat than cooked tubers, Wrangham sees his work as expanding on the ideas of Aiello and Wheeler concerning food, guts, and brains. With Rachel Carmody leading experiments, mice became subjects that were offered meat and tubers separately in three different preparations (raw, pounded to make it easier to digest, and cooked). Mice preferred cooked foods (both tubers and meat) and gained more weight on it, even though the amount of food in the three preparations was identical (Carmody, Weintraub, & Wrangham, 2011). In a parallel study, mice were offered peanuts prepared by cooking and by blending. In this project the team investigated whether mice would gain more weight on cooked rather than raw plants containing fat, as they had with tubers and meat, and they did (Groupman, Carmody, & Wrangham, 2015). These experiments confirmed the energetic benefit of cooked food.

Briana Pobinar (2016) tested part of the Aiello and Wheeler hypothesis by following lions on a private game reserve in Kenya as they killed zebras. She picked up bones left behind and measured the amount of food remaining on bones and in marrow. Surprised by the large quantity, she reasoned that if patterns from today's animals reflect those of two million years ago, there would have been plenty of food for scavenging hominins. Prior research had established that some early hominins scavenged land animals in the early Pleistocene, and Pobinar (2016) reported archaeological evidence at the 1.95 MYA site of Koobi Fora, Kenya, indicating that hominins were eating aquatic animals such as turtles and fish.

Cooking, of course, requires fire. For years, archaeologists have argued about how to determine whether evidence of fire at a site is valid, and if valid, whether it indicates control by humans. Skepticism always follows pushing back dates of prehistoric events (consider the timing of people entering the Americas), but evidence has continued to accrue that hominins have used fire for at least the last million years. Pobinar (2016, p.116) wrote that "the first solid evidence comes from a one million-year-old site called Wonderwerk Cave, in South Africa." Jagged edges of ash within the cave indicated to her that the fire occurred where ash was found within the cave, not blown there from a natural fire outside.

Food choice and cooking hypotheses are examples of anthropologists successfully applying energetics to explain behaviors that have had profound evolutionary consequences. Wrangham's book not only makes the case for cooked food over raw food but suggests that cooking led to the gender division of labor, common in most societies, of men providing food and women cooking and serving it.

The epilogue in *Catching Fire* titled "The Well-Informed Cook" suggests ways that modern cooks can counter inherited eating preferences for foods that provide too many calories for today's needs.

NEANDERTALS, MODERN HUMANS, AND OTHER HOMINOIDS

The symposium "Energetic Studies in Hominin Evolution," organized by Karen Steudel-Numbers in 2007 at meetings of the Paleo Anthropology Society and published in 2009, explored topics central to understanding how hominins and other hominoids differ energetically. Patricia Kramer and Adam Sylvester (2009) explored ways to consider limb length vs. other factors affecting the energetics of bipedalism in hominins.

Also in that symposium, Josh Snodgrass and William Leonard (2009), who have developed energetics analyses with modern Siberians (Leonard, Snodgrass, & Sorensen, 2005), compared models of Neandertal energetics with estimates of the hominins who replaced them in Europe. Their paper and one by Andrew Froehle and Steven Churchill (2009) used energetic models of Neandertals to suggest problems that may have caused their demise. Both papers concluded that Neandertal biological and behavioral adaptations, which developed over several hundred thousand years in a very harsh environment, did not compete well with a more efficient biological and behavioral system brought to Eurasia by a modern human population in the late Pleistocene.

Considering Neandertal energy requirements as high compared with that of modern humans is especially interesting in view of Herman Pontzer and colleagues' paper "Humans, the high-energy ape: hominoid energetics and life history evolution" at the 2015 meetings of the American Association of Physical Anthropologists (Pontzer, Brown, Dunsworth, & Ross, S., 2015). The entire symposium, "Energetics in Human and Non-Human Primate Evolution: Moving from Theory to Empirical Tests," organized by Christopher Kuzawa and Herman Pontzer, focused on energetics and life history. In a 2016 Letter in *Nature*, Pontzer's team expanded on ideas explored in the 2015 symposium by providing empirical data showing that energy requirements of chimpanzees, gorillas, and orangutans are consistently lower than ours (Pontzer, Brown, Raichlen, Dunsworth, Hare, Walker, Luke, Dugas, Durazo-Arvizu, Schoeller, Plange-Rhule, Bovet, Forrester, Lambert, Thompson, Shumaker, & Ross, 2016). If we add to the metabolic energy we burn as biological beings the energy of fossil fuels that we consume with technological devices, the comparison is stark indeed.

Previously I cited a comparison of the high energetic needs and productivity of placental mammals versus the lesser needs and productivity of marsupials. Predominance of placentals has been interpreted as success because they are numerous in many regions where energy is abundant. I have to question whether this is how we should interpret the high energy costs of the human brain, the abundance of hominins, and the shrinking numbers of our hominoid cousins. Is this pattern of dominance by high-energy animals sustainable? If not, what can be done to make it so, or to make it different?

CLIMATE, HUMAN VARIATION AND ENERGETICS

Bergmann's and Allen's Rules

Anthropologists seeking to explain human geographic variation often focus on how the body responds to heat, whether the need is to dissipate or conserve it. Even before Charles Darwin (1859/1964) published *On the Origin of Species,* biologists were considering how plants and animals fit within their climates. In the nineteenth century, two ecogeographic 'rules' were developed from observations of morphological variation in animal populations, Bergmann's Rule and Allen's Rule, and for years they have been applied to human variation. Carl Bergmann in 1847 posited that animals living in cold climates tend to be larger than related species in warmer climates, while Joel Asaph Allen used the same logic in 1877 to consider linear vs. rounder body shapes as adaptations to hot or cold climates. Having more surface area helps to dissipate unwanted heat while an appropriate adaptation to a cold climate would be to minimize surface to conserve heat. Bergmann's Rule was extended to include variation among populations of the same species, and because humans are the mammalian species with the widest geographical distribution, our species is an excellent subject to examine.

Chief among climatic variables are temperature and humidity, which have been related to limb lengths and proportions among limbs, height and weight, cranial measures, chest and trunk size, and facial measurements. Ratios or indices have been used, particularly in the pre-computer era, because they can be analyzed with simple statistics and to some extent they control for size differences between populations and between genders. Indices include the cranial index (cranial breadth as a percentage of length), nasal shape (breadth as a percentage of height), sitting height as a percentage of total height, and the ratio of proximal to distal limbs. Examinations of empirical data, done to determine whether predictions of the Bergmann and Allen Rules hold, tend to validate the rules to a statistically significant extent, but each population shows a wide range of variation. One example is Ken Beals's (1972) study of the relationship between head shape and climate, which used data gathered by many investigators worldwide to test the hypothesis that broader heads are associated with colder climates.

Physiological tests have been used to determine, for example, whether Arctic-dwelling people actually can tolerate temperatures that cause frost-bite in people with ancestry in warm regions and, if so, whether this ability is inherited genetically, gained during childhood in individuals growing up in the habitat, or acquired by short-term exposure and use of appropriate clothing and other material culture. Concepts have been extended to prehistoric populations as represented by skeletal material as ancient as the early Pleistocene and as recent as the Late Pleistocene. Though energetics as such has not always been mentioned, it is implicit and over time has become more explicit.

High Altitude Adaptations

Specific genetic adaptations have been looked for particularly where physiological and climatic challenges are extreme. Many teams have successfully studied aspects of adaptation to high altitude. Studies have shown all three types of high altitude adaptations: short-term headaches and breathing stresses, followed by increases in red blood cells; impacts on growth for those who enter the environment as children; and hereditary changes for those with deep ancestral connections. Comparisons between Tibetan and Andean populations describe physiological adaptations that differ in the two locations (Beall, 2007; Harris, 2015). These adaptations presumably have a slightly different genetic basis though they have developed through natural selection responding to the same challenge, i.e., adapting to low levels of atmospheric oxygen over varied lengths of time.

Energetics of Nasal Structures

Anthropologists have studied the relationship between nasal form and climate for more than a hundred years, beginning at least as early as 1913 when Arthur Thomson read the paper "The Correlation of Isotherms with Variations in the Nasal Index" at the Anatomical Section of the International Medical Congress. A second author was added to the expanded paper, published ten years later (Thomson and Buxton, 1923). Subsequent reports on the climatic distribution of nasal shape have identified tall, narrow nasal forms in cold, dry climates and short, broad nasal forms in hot, humid climates, just as Thomson and Buxton did. Their paper offered anatomical descriptions of the features of the inner nose, including the conchae (or turbinates). These vary in size and placement, maximizing exposure of air to mucous membranes in tall, narrow noses and minimizing exposure in broad, short noses. Nearly a century ago, these researchers provided clear descriptions of how the nasal system warms and moisturizes air. Their statistical measures differ from later ones that employ computer analysis, but conclusions are much the same. Their paper is one of very few that discusses benefits of a broad nose in quickly expelling hot moist air.

Re-reading their paper recently, I wondered why so many scholars, including myself, bothered to conduct additional studies, though each new paper has offered a slightly different approach or has examined a different population. My initial work, beginning in 1997, was to gather data from 518 crania from diverse climatic zones, which I did using six museum collections. Results confirmed prior work by many investigators. In 2002, I realized that a deeper explanation of the relationships could lie with energetics and the study of how nasal morphology adapts to conserve energy in different climatic regimes.

As applied to nasal shape and structure, energetics theory posits that natural selection favors nasal (mid-facial) adaptations that are energy-efficient in a population's native habitat. An evolutionary approach requires thinking about life in prehistoric societies where people do considerable physical work and food is not always plentiful. The idea of doing physiological experiments to understand this component was not new; it was suggested 40 years ago by Ted Steegman in a paper in Albert Damon's book *Physiological Anthropology* (Damon, 1975; Steegman, 1975). I did two studies. The first developed protocols for nasal measurements and tested them in a sample of 50 subjects whose energy consumption was measured using nose-breathing and mouth-breathing separately while subjects were lying down, sitting up, and doing a moderate cycling exercise (Hall, 2005). The second was a pilot study with additional measures occurring in a climate chamber simulating humid heat and dry cold in addition to indoor lab conditions (Hall, Halliwill, & Bridgmon, 2012). Details about these studies are provided elsewhere (Hall, 2016). As breathing is the *sine qua non* of living, an expansion of this project could help us understand some of the challenges that warming climates will present, plus help to explain current morphological variation.

ENERGETICS AND CULTURAL EVOLUTION – LESLIE WHITE

For six years a political scientist colleague and I taught an undergraduate course that in effect was a primer on sustainability. We began by reading Thomas Malthus's (1798/1970) *An Essay on the Principle of Population* and continued with chapters from E. F. Schumacher's (1973) *Small is Beautiful*, Charles Darwin's (1859/1964) *On the Origin of Species*, Paul Ehrlich's (2000) *Human Natures*, Leslie White's (1949) *The Science of Culture* (1949), and Herman Daly's (1973) *Economics, Ecology, Ethics; Essays Toward a Steady-State Economy*.

[see TABLE II ----- Human Time Line, p. 34-35]

For an outline of their species' evolutionary path, I provided Table II, a human time-line focused on technology and energy sources. We reviewed when new technologies opened access to ever-greater supplies of energy that led to population and economic growth and to settlement in varied ecosystems around the globe. White's chapter "Energy and the Evolution of Culture" proposed that culture evolves as societies gain control of greater amounts of energy. From a twenty-first century perspective, the term "cultural evolution" may seem to imply automatic improvements over time. White, however, makes it clear that he did not mean moral or mental progress, nor does cultural evolution guarantee stability or survival. Rather, to White, it implied *more* of everything: larger populations, more complex political organization, greater lethality of weapons, larger and more elaborate buildings, etc. He viewed these increases as the result of new technologies that provide access to new sources of energy, as implied in Table II.

The cultural evolution White described occurs despite growth and decline of regional superpowers that ultimately exhaust their resource base. During times when new sources of energy are developed and exploited, the momentum of growth appears unstoppable, as if the new sources of energy and the political organizations that support them will never fail. But failure is inevitable.

Historians have long investigated causes of the decline of empires, while recent themes have been discussed by Paul Ehrlich (2000) and Jared Diamond (2005).

Writing in 1949, White had great concern about what atomic energy might lead to. He was no Pollyanna and he described what he saw, putting it in the form of a symbolic equation: E x T → C (Energy times Technology leads to Cultural Development). White's materialist approach to world prehistory did not play well in anthropological circles at the time, however. The period after World War II was one of optimism and growth; perhaps White's writing seemed dogmatic to anthropologists of the 1960s and 1970s, or they may have felt it left out individual choices that anthropologists had described or wished to see. If I had not taken a graduate course taught by a former student of White's, I might never have been exposed to his ideas at all.

HOWARD T. ODUM, ENERGETICS, ECOLOGY, AND SYSTEMS

Howard T. Odum's name is associated with systems ecology and mathematical models to represent energy flow, and his book *Environment, Power, and Society* (1971) received attention from scientists in many fields. He presented basic concepts of measuring energy flow and then broadened his scope to human systems, showing how inputs and outflows of materials and energy apply whether systems are ecological or social. Examples include societies extensively studied by anthropologists, such as island-dwelling peoples of the Pacific and pygmy populations in complex rain forests. Their life ways, he said, exemplify stable systems based on solar energy. By being mobile and following the natural cycles of their environments, they do not perturb the system, he thought, but may help to maintain it. These sustainable societies allowed Odum to decry ecological problems posed by industrialization and posit views concerning how and why large civilizations crash.

Odum used the heading "Potatoes Partly Made of Oil" for a section describing unsustainable consumption of fossil fuels. He summarized the concept: "One of the results of industrialization based on the new concentrated energy sources was abundant food rolling out from huge fields which were sowed with machinery, tilled with tractors, and weeded and poisoned with chemicals" (Odum, 1971, p.116). Farming based on fossil fuels, he wrote, produces more food and more people, a conclusion White would have agreed with. Odum in this 1971 book also anticipated legal developments exemplified by court cases such as those brought in 2016 by Our Children's Trust. Using the public trust doctrine (Wood, 2014), such cases argue that natural resources, e.g., clean air and water, are part of the public trust that governments at all levels are obliged to protect for future generations. Odum (1971, p. 299) wrote, "Basic to many of the legal battles underway and developing in the defense of the environment is a long ignored constitutional freedom – the right to a safe life-support system."

ANTHROPOLOGICAL RESPONSES TO ODUM'S CHALLENGE

One example of a response to Odum's call to confront challenges posed by industrialization is found in anthropologist G.A. Harrison's (1982) edited book *Energy and Effort*. In the preface, Harrison tells why the Society for the Study of Human Biology chose the energy theme for its symposium in 1981:

> One of the important areas of growth in human biology, and especially biological anthropology, in recent years, has been in human ecology. A knowledge of the way human beings affect and are affected by their environment is not only of great intellectual interest in itself, but is also of some substantial practical concern to environmental management, health, and population regulation...There is nothing a community does, or does not do, which hasn't an energy implication, and much of what it does is actively concerned with energy acquisition (Harrison, 1982, p. vii).

Yet not all participants in that symposium 36 years ago agreed with the editor or with Odum. P. Burnham in a chapter titled “Energetics and Ecological Anthropology: Some Issues” took the position that Odum “provides an extreme and much-discussed attempt to understand the entire world system in energy terms” (Burnham, 1982, p.229). Burnham’s concluding paragraph offers a broader condemnation of energetic studies: “In fact, I would argue that few studies in the field of anthropology have contributed less to our understanding of the ‘existential game’ than have energy-flow studies” (Burnham, 1982, p.239).

By contrast, speakers Brooke Thomas, S.D. McRae, and Paul Baker agreed with Odum’s perspective in their paper, “The Use of Models in Anticipating Effects of Change on Human Populations” and directly addressed the points that Burnham raised:

> In a discipline such as anthropology, where understanding human biological and cultural phenomena from a systemic point of view is of central concern, it is discouraging to find that paths of inquiry are so easily dismissed... In summary, the utility of energy-flow analysis lies in its ability to quantify relationships between principal components of human systems (Thomas, McRae, & Baker, 1982, p.277).

Instead of offering a comprehensive theory or methodology as have Leslie White and Howard Odum, some anthropologists have nonetheless applied energetics to help them understand local variations in human bio-cultural adaptations. Stanley Ulijaszek’s (1995) *Human energetics in Biological Anthropology* alludes to this trend that in effect blends cultural ecology with biological adaptations: “The use of energetics in biological anthropology began with the ecosystemic approach but has been used in less holistic ways to examine processes of human adaptation and adaptability" (Ulijaszek, 1995, p.1). Many anthropologists have incorporated energetics concepts into research on how populations adapt to scarce resource environments. An example of this approach is found in the work of Catherine Panter-Brick who has compared life-history trade-offs in different populations living at high altitude in Nepal (e.g., Panter-Brick, 1997). Many times biochemical and nutritional or other biological measures of health complement studies of behavioral choices.

CONCLUDING THOUGHTS

Earth's living things have a long evolutionary history, and a review of their journey engenders deep feelings of respect. Evolution on Earth can appear wondrously fortuitous, but we also recognize core principles that have shaped and still govern life on our small planet. Energetics and ecology – the efficient use of available energy and the ability to co-evolve with other species and the material conditions of the immediate environment – have mattered for survival. Organisms that use more energy than circumstances provide do not fare well. These lessons seem clear, yet we need to ask this question: has the human lineage become an exception? Or are we living on borrowed energy, and perhaps on borrowed time? Seven billion people expect their home planet to continue to provide resources, energy, and a hospitable habitat. Anthropologists who represent the branch of science most focused on the evolution and behavior of *Homo sapiens* must consider what demands we as a species are making on our planet, and how long we can get away with it.

Earth scientists in fields such as ecology, atmospheric science, and oceanography have dominated discussions of anthropogenic climate change. Neither cultural nor biological anthropologists have taken on the challenge of re-designing modern society as Odum advocated, but some have represented people whose habitats and livelihoods are being injured by climate change. At their 2016 meetings the Society of Applied Anthropologists included papers describing this work, and no doubt other societies are doing so or planning to do so. Are these efforts of world citizenship sufficient? What else can we do?

Beyond participating as concerned citizens, I believe anthropologists need to discuss what we should be telling our students, each other, and our fellow humans about what we know of evolution on earth, and of past environments and species, especially those in our own lineage. We know change is inevitable. How did we become the species we are? What happens now? Asking tough questions is the anthropologists' role – our calling. We are uniquely qualified to deepen and broaden the stories and details of Earth history, even beyond the history of life, not to replace other disciplines but to illuminate the intimate inter-connections that exist among the sciences. If there is to be a future for our own kind, we would be wise to incorporate our species' life history into a much broader history. We should appreciate our fellow species, from the smallest microbial form to the largest and most charismatic, and respect their fragility along with ours. We must appreciate Earth's materials, which we call non-living but now know are made of the same stuff as ourselves, which we call living. Perhaps even more consciously, we must accept and honor the sun's energy and the hard-won oxygen produced by life itself, now available to all of us within the atmosphere that surrounds and protects us.

Many authors in diverse fields have provided profound insights about the Earth and Universe that we occupy. Over recent decades, details and understandings have increased exponentially. Many have offered observations and admonitions similar to those of Paul Falkowski (2015, p. 144), “In the landscape of large organisms with complex interactions, humans are the new animals on the planet and have rapidly become the new evolutionary Bolsheviks. We tend to think we are so different from other organisms that we can ignore the history of the planet. But can we?”

We have seen in hominin development that natural selection favors efficiency of structures and behavior patterns. Those that are efficient have been favored over those that are less efficient. As humans have added ancient finite energy resources to the total energy budget of our extended species, our activities and our collective bodies have impinged on the habitats and resources of many other life forms, fellow travelers on the planet. Earth’s history shows that our atmosphere has developed as a protective resource on which current life depends, and that our atmosphere has an immense capacity for change. What kinds of change are compatible with our species? Are we a threat?

Here is how Andrew Knoll (2003, p. 246) concluded *Life on a Young Planet*:

> Copernicus and Darwin profoundly altered the human sense of self. We do not live at the center of the universe, and we cannot claim the privileges of special creation. In coming decades, planetary exploration may even show that we are not unique or, at the very least, not alone. But whatever astronomy and evolution may take away, ecology restores. On this planet, at this moment in time, human beings reign. Regardless of who or what penned earlier chapters in the history of life, we will write

the next one. Through our actions or inaction, we decide the world that our grandchildren and great grandchildren will know. Let us have the grace and humility to choose well.

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Table I. Geologic Time Line

Eon; MYA	Era; MYA	Period	Features
Hadean; 4600 - 4000		No geologic periods	Formation of solar system, including planets
Pre-Cambrian; 4000 - 542	Archean; 4000 - 2500	Early	Atmosphere of methane & ammonia; earth crust; plate tectonics originates; earliest fossils in Western Australia and South Africa
		Middle	
		Late	
	Proterozoic; 2500 - 542	Paleoproterozoic	Great Oxidation Event ~2400 MYA
		Mesoproterozoic	Snowball Earth: Global glaciation episodes hypothesized in part of the Proterozoic

		Neoproterozoic	First animals, the Ediacaran fossils
Phanerozoic; 542 - present	Paleozoic; 542 - 251	Cambrian	Animals diversify; first jawless vertebrates
		Ordovician	Diverse marine fossils
		Silurian	First clear evidence of life on land
		Devonian	First trees and forests
		Carboniferous	Oxygen estimated as high as 35%; humid tropical climate; coal deposits
		Permian	Insect giantism at end; Pangaea coming together; mass extinction at border with Mesozoic
	Mesozoic; 251- 65.5	Triassic	Pangaea; single land mass, massive ocean
		Jurassic	Dinosaurs dominant on land; first birds
		Cretaceous	Major extinction event at close
	Cenozoic; 65.5 - present	Paleogene	Paleocene: mammal radiation
			Eocene: warm tropical climate; primate dispersal
			Oligocene: primate diversification
		Neogene	Miocene: hominoids disperse
			Pliocene: cooling; hominins develop rudimentary tool-making
		Quaternary	Pleistocene: human evolution and spread of *Homo sapiens*
			Holocene: agriculture and industrialization

Chart divisions are not to scale.
Data are from Canfield, 2014, p. xiv; Kump et al., 2010, p.14; Tarbuck and Lutgens, 2014, p. 11.

Table II. Human Time Line - Technology and Energy

Years B.P.	Biological Group	Range [cumulative]	Energy & Technology	Resource Economy
~-3-4 million	early hominins, e.g., Australopiths	East Africa & South Africa	human physical effort	gathering & scavenging
~2.2 million	+ more species	as above	+ stone tools	as above, possible

				simple hunting
~1.8 million	early *Homo*; possibly early *Homo erectus*	+ Asia, west & south-east	+ better tools	as above
~1.0 million	*Homo erectus*	+ Eastern Europe	+ fire; improved tools	possible cooking
~500,000	archaic *H. sapiens,* e.g., Neandertals	+ more areas in Asia and Europe	+ creative artifacts, likely language	expanded foods, hunting & gathering
~150,000	+ modern *H. Sapiens*	Africa, plus adjacent areas	intensification of above	as above
~50,000	*H. Sapiens*	+ Greater Australia	+ rafts, spears, fiber arts	possible burning of vegetation
~18,000	as above	+ the Americas	+ boats, more tools, bow & arrow, dogs, sophisticated art	+ more game and plants, resource management
10,000	as above	+ higher altitudes within continents	+ agriculture, animal energy, pottery	broadening of human niche
5,000	as above	+ intensity within settled areas	+ writing, some metals and minerals, tools for killing humans & animals	continuing trend to increase and manipulate resources
~2,000	as above	+ high arctic and Pacific islands	+ compass and other clever tools; hunting whales for oil and food	greater trade and transfer of plants and animals; extinctions
~200 - present	as above	+ areas where total provisioning is required	intensive use of stored minerals & devices to process & store food; oil & gas; atomic, chemical & nuclear devices; electricity & computers	greater intensity of these trends; increased manipulation of resources; impacts on total ecosystem

*These are general trends; dates are approximate, with estimates always being updated (and argued about). Note the interdependence of the last columns with concomitant population increases.