Urban metabolism of ancient Caral, Peru

John E. Fernández, School of Architecture and Planning, Massachusetts Institute of Technology (MIT), USA

Abstract

During the 20th century the world's urban population increased by a factor of 10. Global climate change, intensifying resource scarcities and continuing urbanization now define the context within which contemporary cities have become home to one half of the global population. For the foreseeable future, 95 percent of world population growth will be in urban areas and virtually all of this growth will be in Africa, Asia and Latin America (UN-Habitat 2006, United Nations 2008, Montgomery 2008). In addition, we are faced with the reality that growing urban populations have always led to greater affluence and increased resource consumption. Despite claims of the efficiency with which cities use resources, global urban resource consumption trends are generally upwards. For example, in Hong Kong water, food and material consumption increased 40, 20 and 149 percent between 1971 and 1997 (Warren-Rhodes 2001, Fernández 2006). So, what are the prospects for a sustainable urban future?

Given what we already know about urban resource consumption trends and the continuing development of Asia, the prospects for substantial gains in efficiencies in the urban context – in transportation, building energy, goods and services – are difficult to imagine without fundamental transformation. The question remains, what kinds of fundamental transformation are possible?

This project seeks a focused answer to this question by looking both forward and backward. On the one hand, the development of scenarios that propose dramatically more efficient urban systems coupled to reduced demands by urban populations is important work. Much of the work in urban metabolism and sustainable cities is of this type. On the other, analyses of substantial urban centers that were founded and grew to scale under pre-fossil fuel socioeconomic resource regimes may also yield important insights. In fact, the only non-fossil fuel cities that we know of are those that existed before the advent of our current fossil fuel socioeconomic resource regime.

The seed funding from the Holcim Foundation is being employed primarily to advance knowledge in this latter type of urban analysis; the urban metabolism of ancient cities. The focus of this study is the determination of resource flows serving the ancient pre-Inca city of Caral, located north of present-day Lima. Based primarily on archeological data of the economy of ancient Caral, this study will attempt to establish the actual material and energy flows serving the urban population of Caral. The value of establishing this ancient urban metabolism is to use our findings to compare the character and intensity of ancient resource consumption with contemporary urban Peruvian resource consumption. Using fundamental definitions of urban activities, we propose to formulate resource intensity indices based on the material intensity per unit of service framework (MIPS). In this way, useful comparisons can be made that contrast the resource consumption profile of pre-fossil fuel supported urban form with that of contemporary cities. Clues regarding the pathway forward may then be derived from this look backward.

During the 20th century the world's urban population increased by a factor of 10. Despite claims of the efficiency with which cities use resources, global urban resource consumption trends are generally upwards. Given what we already know about these trends and the accelerating urbanization of the developing world, the prospects for substantial gains in efficiencies in the urban context – in transportation, building energy, goods and services – are difficult to imagine without fundamental transformation. The question remains, what kinds of fundamental transformation are possible? This project seeks to analyze a substantial urban center that was founded and grew to scale under a pre-fossil fuel sociometabolic resource regime. The focus of this study is the determination of resource flows serving the ancient pre-Inca city of Caral, located north of present-day Lima. Based primarily on archeological data of the economy of ancient Caral, this study establishes the actual material and energy flows serving the urban population of this Preceramic New World city.

1 Sociometabolic regimes and global materials consumption

The debate regarding the global urban future has been elevated in importance by the academy, business community and government entities and received a great deal of attention in light of ever-increasing critical resource stresses and the coming massive urbanization of the developing world. As the main global driver of socioeconomic activity, cities are now considered in the center of discussions regarding the ability of societies to address the challenges of global climate change and social well-being. Evidence of the intensity of concern about urbanization can be found in the proliferation of green city plans, initiatives, partnerships, rating systems, and other organizations and mechanisms to promote resource efficient urban growth. In addition, the well-known new cities of Dongtan, China and Masdar in the UAE are two of many examples of the enormous investments that have been assembled for the purpose of demonstrating alternative modes to deliver 21st century urban amenities through dramatically more efficient means.

This study of an ancient New World city in Peru is intended to highlight the importance of coupling the notion of a governing sociometabolic regime with the actual physical flows that are generated by that regime. The results of such work bring articulation to the various resource profiles that are likely under any particular sociometabolic regime. Without a rigorous and quantitative assessment of the potential for efficiency while satisfying the basic needs of urban residents, we cannot know the possibilities that are available to us in the creation of green cities. Studying the urban metabolism of a pre-fossil fuel city, and articulating its resource profile contributes to understanding how a large settlement of the future may be able to deliver goods and services in a sustainable way.

1.1 Sociometabolic regimes

The work of this study has been guided by the notion of sociometabolic regimes as introduced and developed by Sieferle (2001) and others (Fischer-Kowalski and Haberl 1997) and recently used by Krausmann et al. (2009) in a global assessment of the dynamic equilibria of society-nature interactions. The classification of sociometabolic regimes as established by Krausmann et al. (2009) is thus adopted here. This notion is particularly useful as an umbrella concept in articulating the urban metabolism of an ancient city.

Today, almost every city in the world is served by the dominant *industrial sociometabolic regime*. This regime is largely characterized by the social and technological changes brought about by the use of fossil fuel energy carriers as the dominant energy source (Wrigley 1988)(Krausmann 2008). As a result of the transition from an agrarian to an industrial sociometabolic regime, energy became cheap and plentiful, land use was decoupled from local energy constraints, and industrial production produced an explosion in per capita material and energy consumption.

The preceding, pre-fossil fuel sociometabolic regime, the *agrarian sociometabolic regime*, was constrained by the production limitations of solar energy. A vast majority of the product of an agrarian regime is biomass that is used for construction, heating, food, textiles and other products. Limited by available sunlight, the quality of soil and the availability of nutrients, limitations of human and animal power, climate and other local factors, the agrarian regime naturally optimizes for long-term productivity of land while limiting the population density that can be sustained.

A useful perspective of urban futures regards the industrial sociometabolic regime as essentially transitional; that is, between the long period of agrarian regime dominance (roughly 10,000 years) and the (hopefully) long post-fossil fuels future, the industrial regime is but a short and intense period of exploitation of a limited resource and cannot be considered as a stable and sustaining regime. In this sense, a future city that is truly sustainable – or at the very least, sustainable in a mode not dependent on fossil fuels, may exhibit some attributes that may be found in pre-fossil fuel urban centers. However, it is likely that new, emergent resource profiles that take advantage of technological advances and heightened demands for services will substantially expand the possibilities of urban metabolism under a post-fossil fuel sociometabolic regime.

1.2 Global resource extraction

Our infrastructure – roads, power and water networks – along with the buildings that we inhabit and utilize to house the processes and products of industrial production demand the vast majority of mineral ores extracted and converted into useful metals and alloys. Our "built environment" is literally the largest in-use repository, or *stock* that we humans have accumulated. Some studies estimate the accumulation of mineral stocks in the built environment of developed regions approaching several hundred tons per capita (Hashimoto et al. 2007). To serve this stock we have been extracting minerals from relatively evenly and widely distributed global sources in the developed and developing regions of the world and directing their flows to concentrate into a small number of dense urban population centers. In-use stocks of primary metals are now greatly concentrated in cities. In fact, 25% of in-use primary metals can be found in only three large urban regions; on the eastern coast of the US from Washington to Boston, from England through Germany and northern Italy, and in the region of South Korea and Japan (Rauch 2009).

In addition, the intensity of material extraction has proceeded at ever-increasing rates. In fact, there has never been a more frenetic period of resource prospecting, extraction and processing than during the last 100 years. In a recent study, it was found that global materials use during the 20th century increased by 8 times while population grew four-fold and GDP ballooned 20-fold (Krausmann et al. 2009). The last half century after WWII, especially the years between 1945 and the oil crisis of 1973, saw the largest acceleration in the extraction of materials and eventually led to a global per capita materials use double that of 1900. During the 28 years after WWII, overall per capita materials use increased by 50% and 340% for nonrenewable materials (Krausmann et al. 2008). This last figure reflects the fact that many economies decreased the amount of relatively low-value and fast thoughput renewable biomass and replaced it with high-value nonrenewable metals and other minerals.

Humans now use approximately 60 billion tons of material every year, an amount that roughly rivals the total global terrestrial net primary production; the natural production of all plants on earth (Haberl et al. 2007). Yet, the challenging prospect of vastly increasing materials use with the development of India and China is looming large in many academic and governmental circles. During the last century, increases in energy and materials consumption were closely correlated to population growth in the developing regions of the world. In the next several decades, industrial development accompanied by massive urbanization and the spread of middle-class affluence will drive materials use at rates significantly greater than population growth. The study of this societal metabolism holds special importance and promise in urban centers, thus the emergence and significance of *urban metabolism*.

2 Urban metabolism of an ancient metabolic regime

Much work that utilizes the notion of sociometabolic regimes is focused on spatial scales at the large regional and national scales.

This paper intends to couple the important attributes that can be assigned to a particular sociometabolic regime with the actual metabolism of an urban context. Therefore, this work intends to illustrate the material and energy flows that are a result of the settlement and growth of an urban center. To do so, an urban metabolism framework that is being used here will be detailed below before it is applied to the ancient city of Caral.

2.1 Urban metabolism framework

The urban metabolism framework used here has been developed by the author and students at both the Massachusetts Institute of Technology, USA and the Instituto Superior Técnico in Lisbon, Portugal.

First, the framework intends to capture a holistic understanding of the physical flows serving the urban context by using the method of material flow analysis (MFA). MFA is dependent on a high level of physical unit accounting of all major flows and a resolution of those flows to an extent that a credible mass balance can be documented and verified. In other words, what goes into an urban center (whether it be electrons, wood, water or air) can be balanced with comes out plus what has remained inside. Losses in the form of heat and distribution losses must also be accounted for.

Second, the basis for driving the urban socioeconomic engine is to be found in the physical requirements for providing urban residents with all that is needed to engage in three fundamental urban activities; the construction and inhabitation of the built environment, the production and distribution of all goods and services, and the construction and operation of transportation.

The framework presented here delineates energy and material flows devoted to these three broadly inclusive sets of urban activities (see Figure 1):

1. the provision of habitable space (the built environment, ua_1),
2. the provision of goods and services of all types (products, ua_2) and,
3. the provision of the movement of goods and people (transportation, ua_3).

These urban activities are formulated as ***provisions*** of urban living and working. That is, the city is conceived of as a collection of necessary and sufficient provisions of habitable space, goods and services (especially air, water, food, critical materials and waste removal) and transportation. This formalization is intended to provide a robust intellectual and operational link to the main theoretical assertions of economic economics and urban ecology. Specifically, spatial equilibrium is organized according to the production of firms and workers (goods and services) and the costs of housing (built environment) and transportation. These explicit links lend important guidance in the ongoing project to link economic models of urban growth and development with models of resource consumption that take into account natural cycles and biogeochemical processes.

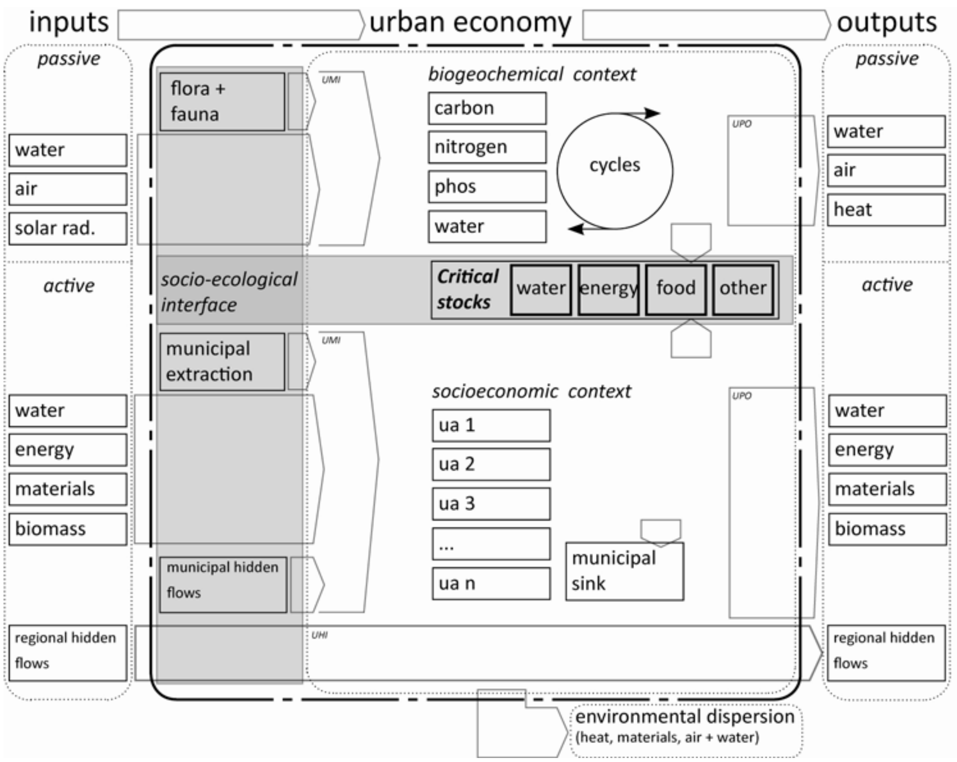

Figure 1: Urban metabolism framework

Third, the urban metabolism framework used here incorporates the interaction with the biogeochemical processes that influence the urban context and the actual physical location, layout, network pattern and other spatial configuration of the city. The latter is referred to here as the urban morphology.

The product of this study is a dynamic, simplified model of the urban metabolism of the ancient city of Caral. The modeling of urban systems and processes has been carried on a range of levels by a diverse set of researchers from many disciplines. Simplified models are able to capture complex urban scenarios in a useful way. The development of a simplified model of urban metabolism can illustrate:

1 the bulk of energy and material flows prompted by urban socioeconomic activities,
2 the overall relationships that characterize urban biogeochemical processes,

3. primary interactions between socioeconomic and biogeochemical activities, processes and cycles within the architecture of an integrated stock and flow model coupled to a system dynamics module,
4. reasonable results that provide guidance in delineating critical positive or negative behaviors of the urban zone.

The model of Caral was produced using system dynamics software (Anylogic ®) incorporating a linked stock-flow architecture that accounts for all major flows.

2.2 Caral Peru

Peru is a country of 29.5 million people, located at 10 00 S, 76 00 W, in the southern hemisphere on the South Pacific coast of the continent of South America. The total land area of the country is 1,285,216 square kilometers of extremely varied terrain and climate from the arid and flat desert coastal plains of west Peru to the temperate and frigid climate of the Andes mountains and the tropical eastern lowland jungle of the Amazon basin. Natural resources include substantial reserves of copper, silver, gold, iron,phosphate, coal, petroleum and natural gas. Peru is also endowed with a 2,414 km long coast with a territorial water claim of 5,220 square kilometers.
Peru is highly urbanized; 71 percent of the population lives in cities (data as of 2008). The largest city, Lima is located on the flat Peruvian coastal plains and within the river valleys of the Chillon, Rimac and Lurin rivers. The city accounts for almost one third of the national population and almost one half of GDP.

The focus of this study is the ancient city of Caral, now a sprawling archeological site of enormous historical and scientific importance. Ancient Caral was founded and grew to size long before the wars of conquest were waged by the Spaniards against the Inca. As the major urban center of the Late Archaic or Late Preceramic Period, Caral was a complex and highly hierarchical society with a well developed formal urban core supported by houses of various types and sizes.

Caral was the earliest complex urban society in the New World. Though located in an arid climate, the topography of Caral and the Supe Valley allowed for easy irrigation for food and textile crops. A rich mix of crops formed the basis of the economy of the city. Ancient Caral was discovered by the preeminent Peruvian archeologist, Dr. Ruth Shady (Shady 2000, 2001, 2003).

Located below the equator at 10° 53' 25.15" S 77° 31' 8.00" W, Caral lies approximately 142 kilometers north-northwest of Lima. The ancient city is situated in the Supe River valley. From the main archaeological site the river runs approximately 22.5 kilometers north and west into the Pacific Ocean.

2.3 Urban metabolism of Caral

The economy of Caral was based on a mixture of agriculture and marine harvesting. There has been some debate concerning the exact nature of the exploitation of marine resources, whether it occurred through the direction involvement of residents of Caral or through trade between Caral and a series of coastal fishing villages. For the purposes of this study, an element of marine biomass is included in the Caral economy.

From archeological survey and analysis, much detail can be derived regarding the actual physical composition of the economy of Caral. The three fundamental urban provisions of the built environment, transportation, and material goods, were secured by an economy substantially dependent on solar energy.

The built environment was provisioned with local materials; sun-dried adobe, mud and other kinds of earthen materials used for blocks and walls, reinforcing caña brava (Gynerium sagitatum), totora (Scyrpus sp.), small amounts of woods, charcoal, shicra bags and other textiles. Transportation of people and goods of all kinds was powered by animals or undertaken on waterways.

The goods produced and consumed by the residents of Caral primarily derived of the agricultural production of the settlement. Domesticated plants recovered from surveys conducted at Caral include:
cotton (Gossypium barbadense), squash (Cucurbita sp.), beans (Phaseolus vulgaris and P. lunatus), guava (Psidium guajava), pacay (Inga feuillei), camote (Ipomoea batatas), avocado (Persea americana), chilli (Capsicum sp.), lucuma (Pouteria lucuma, formerly Lucuma obovata), and achira (Canna edulis).

Evidence has also been found that the following animal biomass was part of the economy of Caral: clams (Mesodesma donacium) mussels (Choromytilusc horus and Aulacomya ater) anchovies (Engraulis ringens) and sardines (Sardinops sagax).

Therefore, the sociometabolic regime under which Caral was founded and grew to substantial size and population can be characterized as fundamentally agrarian with a substantial marine biomass component. Some countries today exhibit a similar metabolic profile, though all have an essential coupling of low population density and development status (See Table 1). Caral was a dense urban center and in that respect cannot be compared with any but the most remote and technologically limited villages and towns in the world. Certainly no dense and large urban center today qualifies. It is not surprising to note that applying an MFA analysis to Caral reveals that the overall urban metabolic throughput of the ancient settlement is very much less intense than almost every kind of contemporary city.

The comparison with contemporary urban centers must take into account the very broad range of development levels and population densities to be found in cities worldwide. The classification offered by Krausmann et al. is used here and consists of the following designations:

Table 1: Country designations based on development status and population density (adapted from Krausmann 2008)

Designation	Countries
High- density industrial (HDI)	Europe, Japan, South Korea
High-density developing (HDD)	China, India, Central America, some Africa
Low-density industrial New World (LDI-NW)	North America, Australia, New Zealand
Low-density industrial Old World (LDI-OW)	Former Soviet Union, Scandinavia
Low-density developing New World (LDD-NW)	South America
Low-density developing Old World (LDD-OW)	Northern Africa, Western Asia, some Africa

3 Results

While it is very clear that the urban metabolism of an ancient city approximates in some important ways that of a contemporary urban center highly dependent on an agrarian sociometabolic regime, the comparison is only useful in limited ways. A general result of this study is the utility of making comparisons between ancient pre-fossil fuel cities and contemporary urban situations in Low-Density Developing New World Countries (LDD-NW).

First, both the ancient and contemporary cities of a LDD-NW country host fairly low material and energy use per capita while highly dependent on natural resource extraction. For obvious reasons the mechanized contemporary extraction occurring at massive scales and oriented toward international trade vastly outwieghs the natural extraction serving ancient cities.

Second, per capita consumption of critical resources, such as water, carloic intake and basic clothing needs are similar in the contemporary (LDD-NW) and ancient contexts.

Third, a comparison oft he consumption of non-critical goods and services shows quite different material througput between the Caral and LDD-NW scenarios, with the LDD-NW consumption vastly outstripping that of Caral in significant ways. Metals, polymers and composites of various kinds, some ceramic materials and some elements of biomass are found in much larger quantities in LDD-NW contexts than in Caral.

Finally, earlier in this paper it was stated that it is likely new, emergent resource profiles that take advantage of technological advances and heightened demands for services will substantially expand the possibilities of sustainable urban metabolism under a post-fossil fuel sociometabolic regime. These new resource profiles will closely resemble those of the agrarian regime with two important differences.

First, expanding technologies for land transportation will take advantage of important symbiotic relationships with the power grid, renewable energies and building performance. However, these new modes will not be able to curb the contraction of the intensity with which transportation services are in demand today. Additionally, water transport for short, mid and long distance trade and personal transport will again become dominant.

Second, the diversity of material products will diminish as measured in terms of the bulk of those materials transported and consumed by residents in cities. People will have less choice of the wide range of diverse products composed of diverse materials than found in most urban centers today.

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