Human macroecology, energy use scaling and the sustainability of cities: A look at Latin America

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Abstract

We take a human macroecological approach using energy as a fundamental currency to quantify the emergence and future sustainability of urban societies globally with a special look at Latin America. Energetic scaling analysis showed most modern humans in cities in Latin America and elsewhere live at densities of $\sim 10,000$ ind/km², ~ 4 orders of magnitude greater than our hunter-gatherer ancestors (< 1 ind/km²). Meanwhile, modern cities consume $\sim 10,000$ watts per year mostly in the form of extra-metabolic energy (e.g., fossil fuels), ~ 2 orders of magnitude greater than hunter-gatherer biological metabolism (~ 120 watts per year). Further analysis of World Bank data across and within nations over time showed per capita Gross Domestic Product (GDP), energy use, and CO₂ emissions are lowest in predominantly rural countries, increase in urbanizing countries and are greatest in the most urban countries. For the same level of urbanization, Latin American countries show lower per capita GDP, energy use, and CO₂ emissions than global averages. These trends coincide with changes in employment with rural countries employed largely in resource-extraction sectors and highly urbanized nations in service economies. Latin American countries have higher employment in resource sectors compared to most urban countries. Increasing energy use, especially fossil fuel use, underlies urbanization and changes in economic lifestyle. However, these trends cannot continue indefinitely. Latin America, because of its rich renewable and non-renewable resources, may be spared from future uncertainties inherent to complex human-natural systems including climate change, energy scarcity, pandemics, migration, and trade agreements if it chooses to: 1) rapidly transition to renewable powered economies that limit environmental impact, and 2) reduce population and economy size within local and regional renewable biocapacities. A rapid cultural evolution is of the essence.

Keywords: human ecology; metabolic ecology; urbanization; macroeconomics; macroecology; biophysical economics; scaling; global studies

Knowledge Focus: Research or Theory focus

Introduction

Humans are undoubtedly now the major dominant force on the planet (Steffen et al. 2011; 2015; 2018; Ellis et al. 2016). In just ~12,000 years, a blink of an eye in evolutionary time, humans have emerged from being *just* another social mammal to becoming the major driver of physical and biological change on Earth (Crutzen 2002). Pressing socio-environmental issues, such as increasing resource scarcity, climate change, social instability, biodiversity loss, pandemics, and food insecurity require holistic approaches that transcend the physical, biological, social, medical, and engineering sciences with practical recommendations for policy. Here, we synthesize and expand a transdisciplinary human macroecological approach to quantitatively characterize the emergence and future sustainability of modern hyper-dense cities with a special look at Latin America. Our approach uses fundamental biophysical and ecological constraints as macro-indicators (e.g., Burger et al. 2012; Brown et al. 2014; Burger et al. 2017; Schramski et al. 2015; Day and Hall 2016; Pacheco et al. 2016, 2018; Hall and Klitgaard 2018) of strong sustainability rather than solely relying on economic indicators of human capital (Ayres et al. 2001), with great potential for policy development. We previously studied global patterns and underlying biophysical processes driving urbanization, energy use, and sustainability (Burger et al. 2017; Burger et al. 2019). Here we take a closer look at the Americas for several reasons.

First, the Americas have experienced two distinct waves of human colonization; during the late Pleistocene (~15,000 years ago) and a second colonization by Europeans in the last ~500 years (Diamond 1997). The first colonization occurred in a narrow time window with limited subsequent migrations, especially into South America, until European colonization (Rothhammer and Dillehay 2009; Moore 2014; Goldberg et al. 2016). European colonizers diminished Native Americans and reduced their populations both directly through genocide and indirectly through the introduction of novel diseases contributing to the loss of distinct culture and traditional livelihoods (Diamond 1997). These rapid, punctual and recent colonization events to the Americas are considered a unique opportunity for studying the population settlement history of modern humans (Goldberg et al. 2016), and as a simpler contrast to the more complex settlement histories in other parts of the world. Second, the Americas span nearly

the full range of terrestrial, marine and freshwater environments across latitudes and biomes providing an interesting system for comparative geography. For example, the striking similarities in the latitudinal gradient in human population, income, biodiversity and disease (Bonds et al. 2012; Tallavaara et al. 2018; Burger and Fristoe 2018) begs explanation and offers insights into challenges and policies required for socio-economic development. Third, Latin America is rich in natural resources, yet economic growth has been slower compared to the USA and Canada and much more variable among Latin American countries (Hidalgo et al. 2007; ECLAC 2016). Our macroscopic approach, using spatio-temporal patterns and processes, with a central focus on the role of energy in urbanization attempts to shed light on these issues and the policies that can be taken for regional and global sustainability.

Human macroecology uses theory and data to study human systems across scales from hunter-gatherers to modern urban dwellers (Burnside et al. 2012; Burger et al. 2017; Hamilton et al. 2012; Tallavaara et al. 2018; Burger et al. 2012; Burger and Fristoe 2018). Our approach is “macro” in that it uses biophysical theory rooted in fundamental physical and environmental constraints to motivate hypothesis testing through the compilation and analysis of large datasets (e.g., Brown et al. 2011; Hamilton et al. 2012; Burnside et al. 2012; Burger et al. 2017). Doing so attempts to link patterns with processes from local to global scales, and spanning temporal scales from milliseconds required to transmit information in today’s world wide web, to the fossil fuel resources stored on deep geological time that power the current global economy (Burger et al. 2012). It’s “Ecological” in that it uses the fundamental currencies of ecology – energy, materials, and information – and the laws that govern the flows of these commodities between us and our social and physical environments (Odum 1973; Day et al. 2009; Burger et al. 2012; Hall and Klitgaard 2018; Hall and Balogh 2019). We demonstrate how these fundamental principles and general macroecological rules that govern biological and ecological systems broadly, can be used as a baseline to understand unique traits of the human species, the sustainability implications behind their current interconnected societies and to anticipate the challenges and possible policies for achieving future sustainability in a post-fossil fuel world.

Metabolic scaling theory

In recent decades, a general theory of energy or metabolic scaling has emerged as a useful transdisciplinary tool to unify across scales and complex systems (West 2017; Brown et al. 2011). General scaling rules spanning the diversity of life can be useful benchmarks to compare and contrast the human species to the rest of life (Moses and Brown 2003; Burnside et al. 2012;

Hamilton et al. 2012; Burger et al. 2017). The scaling of metabolic energy, in particular, is a useful currency to quantify the trajectory of the human species from being *just* another social mammal to becoming the Earth's most prolific and environmentally impactful species. Across mammals, individual metabolic rate or energy use (E_i) scales predictably with body size (M),

$$E_i \propto M^{3/4}, \quad (1)$$

where large mammals such as elephants and whales have much higher metabolic requirements than do mice (Kleiber 1932). The $3/4$ scaling exponent reveals an economy of scale spanning ~8 orders of magnitude variation in body size in mammals, from mice to whales, where large body sizes require less energy per mass. Human biological metabolism is no exception. We have a metabolic rate of ~100 watts at resting and ~120 watts during active exercise or "field" metabolic rate, precisely where Kleiber's law would predict for a mammal of our size (Burger et al. 2011). This corresponds with the 2,000 kcals per day required to maintain healthy diets (Hammond et al. 2015; Burger et al. 2017; West 2017). Hunter-gatherers power their entire societies using the biological metabolism of about 120 watts per capita that they obtain from food calories through hunting, fishing and foraging.

Unique to modern humans is our ability to harness extra-metabolic energy in the form of fossil fuels and renewables. This increases our per capita energy use from 120 watts of biological metabolism to more than 10,000 watts in high income societies with the inclusion of vast amounts of extra-metabolic energy. Moses and Brown (2003) made the analogy that the amount of energy use per capita consumed by modern humans is equivalent to the metabolic rate of a hypothetical 30-ton ape (Fig 1). The footprint of our colossal appetites certainly has huge effects on ecosystems globally and raises questions for how it can be *sustained* through time (*sensu* Costanza and Patten 1995).

Figure 1. Energy use as a function of body mass in mammals and human societies. Black circles are basal or resting metabolic rate (BMR) for mammals; Grey circles are “field” or active metabolic rate (FMR) for mammals. The open blue circles are per capita energy use among industrial human populations with little variation in body size. Humans have a metabolic rate of 100 watts at resting (e.g., basal) and 120 watts active. The horizontal blue arrow represents median values for modern industrial societies. The blue arrows illustrate the level of per-capita energy use and corresponding hypothetical mass (~30-ton ape). Adapted from (Burger et al. 2011).

Scaling energy use and densities

The scaling of metabolic rate with animal size just described has consequences for many aspects of biological rates and times including life history, population dynamics, and ecology where $\pm 1/4$ and $\pm 3/4$ allometries are observed (Peters 1986; Brown et al. 2004; Sibly et al. 2012; Brown et al. 2018; Burger et al. 2019). One ecological consequence is the inverse scaling of densities (D) of wild mammal populations with size (M), where D scales proportional to $M^{-3/4}$ (Eqn. 2; Damuth 1981). Larger organisms such as rhinos and elephants with higher absolute metabolic rates occur at lower densities than small organisms like mice and shrews with small body sizes and lower total metabolic demands. The maximum number of individuals per unit area (D_{max}), therefore, scales as the inverse of per capita energy demands,

$$D_{max} \propto M^{-3/4} \quad (2)$$

The result is a compensation between size and density. However, densities are not actually limited by body mass directly, but instead by the energetic requirements to support an individual, E_i , of a given body size. Rearranging the allometric relationships in Eqn 1 and 2, energetic scaling theory predicts density scales proportional to E_i to the -1 power.

$$D_{\max} \propto E_i^{-1} \quad (3)$$

This new representation of the scaling of energy use provides a biophysical macro-indicator to understand the emergence of modern cities and energy compared to biodiversity and ecosystem baselines. We previously evaluated this prediction in (Burger et al. 2017) using a combination of open source data for wild mammal populations from the PANTHERIA database (Jones et al. 2009), hunter-gatherer societies (Binford 2001), archeological data (Zimmermann et al. 2009), modern global city data (demographia.com), and energy use data from the Worldbank (Worldbank.org). Here we revisit that analysis focusing on Latin American cities to understand the wide-variation across countries globally, and how Latin American countries compare. Due to data limitations, we assumed constant per capita resource use across cities within countries. This assumption is supported by studies showing linear scaling of resource use with city population size for a few countries including the USA (Bettencourt et al. 2007; Fragkias et al. 2013). Per capita energy use generally varies greater between countries than within, however, this assumption needs to be evaluated with better data from cities in Latin American and globally.

Comparing density and per capita energy use revealed human hunter-gatherers occurred at population densities comparable to or lower than other mammals (Burger et al. 2017). The prediction of the scaling of $D_{\max}$ with E_i is supported for land mammals, where densities scale with individual energy use (E_i) with a slope of -1.08, statistically indistinguishable from the theoretically predicted -1 slope based on the 95% Confidence Intervals (-0.88, -1.27). H-G densities of <1 Ind/km² and 120 watts of energy use is slightly lower than predicted for a mammal of our size but within the scatter of points. In contrast, early agricultural societies pushed these ecological constraints through the incorporation of extra-metabolic energy (Burger et al. 2017). These societies (e.g., ancient Greeks; square symbols), with the inclusion of “beasts of burden” in addition to their own metabolism increased their per capita energy demands to roughly 600 watts (Moses and Brown 2003) and lived on the order of ~100

Ind/km²—two orders of magnitude higher densities than hunter-gatherers. In modern urban societies per capita energy use ranges from one to two orders of magnitude greater than those for H-Gs while obtaining unprecedented densities (Fig 2). The trend clearly illustrates the relation between extra-metabolic energy and the extraordinary densities of modern cities. This rise in urban hyper-densities, which has occurred in just 200 years since the industrial revolution, undoubtedly has major consequences for cultural evolution, economics, and public health including psychology, disease transmission, food security, waste management, transportation, and sustainability (e.g., Burger et al. 2012; Hammond et al. 2015; Nekola et al. 2013; Hall and Balogh 2019). For example, growth rates of COVID-19 cases increase as a function of population size and density of cities in the USA (Stier et al. 2020).

Energy use is directly related to per capita income

In modern human societies, higher per capita energy use corresponds to greater economic activity (i.e., per capita GDP) and with that greater access to education, less infant mortality, morbidity and mortality rates (Brown et al. 2011, Snyder-Mackler et al. 2020). Brown et al. (2014) described how these highly correlated socio-economic indexes are also strongly associated with increased energy use and the United Nations' Human Development Index (HDI). So, it is reasonable to associate the variability in energy use between countries to differences in socio-economic development (Brown et al. 2011; Brown et al. 2014). Across global cities there is a wide range in energy use per capita, from ~400 watts in Dhaka, Bangladesh to more than 10,000 watts in highly developed countries such as the USA, Canada, UK, and Saudi Arabia. It is interesting to note that all Latin American cities fall within an intermediate range of energy use compared to the global distribution. Peru's cities (with over 500,000 inhabitants) stand as the cities that consume less energy per capita, but their ~1,000 watts per capita is still ~600 watts higher than the average inhabitant of Dhaka, Bangladesh. Venezuela's cities appear as the cities with the greatest energetic consumption, with over 3,400 watts per capita. Still, this is one order of magnitude less than the ~14,150 watts per capita demand that stands for cities in Kuwait.

The variation in HDI, per capita GDP and energy use in Latin American countries largely seems to follow the same latitudinal gradient globally (Bonds et al. 2012). This convergent pattern emerges in similar climates in different continents, and in the Northern and Southern hemispheres, and may be driven by ecological drivers of productivity and disease burdens (Bonds et al. 2012; Tallavaara et al. 2018; Burger and Fristoe 2018). Policies related to these

constrains mainly relate to greater investment in public health and non-dependence on natural resources for their economy (Diamond 1997). Indeed, countries in higher latitudes of the temperate southern cone, comprising Chile, Argentina and Uruguay, are currently categorized as “Very high human development index”, and their 2018 per capita GDP in US dollars are the greatest in the region, with Uruguay (\$17,278), Chile (\$15,923) and Argentina (\$11,683) greatly surpassing the region’s average (\$7,531) (WorldBank 2019). Moreover, these southern temperate climate countries achieve greater economic development compared to other large economies in the region such as Mexico (\$9,673) and Brazil (\$9001) that lie at tropical-temperate zones. The Central American countries of Guatemala, El Salvador, Honduras and Nicaragua have ‘Medium Development’, with nominal per capita incomes of \$4,549, \$4,058, \$2,506 and \$2,020, respectively; and only Haiti in the Americas has a ‘Low Development’ based on the HDI, with a per capita GDP of only \$868. The poorest countries in South America are Bolivia (\$3,548) and Paraguay (\$5,821), which one tropical (Bolivia, but with high topography) are both landlocked. In contrast, tropical countries like Cuba (\$8,821), and Colombia (\$6,667) with extensive coastlines have relatively high per capita incomes despite being tropical and Cuba lacking a free market economy. Also of interest is tropical Panamá which shows a relatively high per capita income (\$15,575) and high service economy including trade services via the Panama Canal. Further interesting is the elevational distribution of population and cities throughout the tropics largely along coasts, rivers, or high elevation mountains (Cohen and Small 1998).

Peru, the country with the smallest per capita energy use in Latin America (909.83 watts), shows relatively high levels of urbanization, medium per capita GDP (\$6,941) and ‘High Development’ based on HDI. Hydroelectricity accounts for over 25% of Peru’s total energy use (BP 2019), a significant contribution of what is considered as renewable energy that might be masking the countries’ actual position in the plot and accounting for the greater developmental statistics. However, hydroelectricity in Peru (and other Andean countries) may suffer from uncertainties due to climate change and glacial melt. Also, hydroelectric externalities can also impact the natural system, with potential devastation on local community development if transgressing the ecosystem’s resilience and resistance (Holling 2001, Folke et al. 2002, Downing et al. 2012). Even more, if externalities affect global change drivers (e.g. land transformation, freshwater appropriation and degradation, biodiversity loss), the effects could transgress the local to national or bigger spatial scales (Barnosky et al. 2012; Sage et al. 2019).

Other Latin American countries with over 25% renewable source contribution (also hydropower) are Colombia, Ecuador, Brazil and Venezuela (BP 2019).

Certainly neither per capita income nor HDI capture all dimensions of human well-being and other metrics such as the Genuine Progress Indicator (GPI; Kubiszewski et al. 2013) have been proposed as a more comprehensive approach to understanding the optimal size of the human system relative to the finite biosphere (Daly 2005). The GPI incorporates environmental and social factors in addition to GDP. Its twenty-six indicators seek to determine the net effect of a country's economic production and consumption on its inhabitants' overall health and well-being, by weighting their social costs and environmental impact. Yet, data for GPI and other finer metrics are more challenging to obtain for countries, cities and across time. Venezuela is a case in point. No Latin American country has per capita energy consumption as high as Venezuela at over 3,400 watts per capita, a country whose economy is based on oil production for export. Venezuela is similar to other energy producing countries including those in the Middle East (e.g. Kuwait) and has higher per capita energy use for their level of economic development (e.g., GDP; Moses and Brown 2003; Brown et al. 2011; Brown et al. 2013). These trends are associated with unequal distributions of wealth and/or the great energetic demand that such economic activities require for production, which are later exported abroad increasing GDP, instead of local economies (ECLAC 2016, Ocampo 2017). According to the Worldbank Development Indicators the last report of Venezuela's per capita GDP was \$16,055 in 2014 – higher than any country in Latin America. But it's HDI is medium and the Venezuelan economy has been in economic and political turmoil including hyperinflation and environmental degradation in recent years. So, GDP and HDI clearly do not reflect well-being in Venezuela.

Additional cases in point are Latin American countries that, despite having “High Development” status, have a history of economic crisis (e.g., Argentina) and current signs of large-scale social revolts (e.g., Chile), indicators of great inequalities that are not necessarily accounted for through the HDI index (UNDP 2019). Indeed, the Inequality Adjusted HDI shows Chile to be the second lowest in HDI when measures of inequality (i.e., GINI coefficient) are incorporated. And Chile is not unique. High inequality regions across the globe (e.g. France, Syria, Iran) and in Latin America (e.g. Chile, Ecuador, Venezuela, Colombia, Argentina) are sensitive to changes in energy and transportation prices resulting in recent social revolts (*sensu* Ahmed 2017; Tainter 2019). So, deviations from the macro-trend in the latitudinal gradient in economic productivity offer key insights into understanding how tropical countries have managed to reach higher

development status, whether the diversity in their economic activities and/or investment in public health.

Table 1: A comparison of highest and median density and energy use between Latin American cities and the rest of the World. Energy use includes the energy demanded from food consumption plus extra-metabolic energy use in the form of primary energy sources. Note that the demographia.org dataset does not include all cities <50,000 population for all countries.

	Highest Population Density in city	Highest Energy Use Country	Median Energy Use [Range]	Median Population density in city [Range]	Median Populations Energy flux [Range]
	Individuals/km ²	Watts	Watts	Individuals/km ²	watts/km ²
Latin America	Ibagué, Colombia (18,414 ind/km ²)	Venezuela (3,438 watts per capita; 140 watts from food)	Ecuador 1,337 [909.83-3,438] Watts per capita (lowest: Peru, Highest: Venezuela)	Buenos Aires, Argentina 4,832 [1,490-18,414] (lowest: Sao Luis, Brazil, highest: Ibagué, Colombia)	Chiclayo, Peru 10,450,804 [3,160,568 - 38,084,871] Lowest:Sao Luis, Brazil; Highest: Antofagasta, Chile)
World	Dahka, Bangladesh (47,379 ind/km ²)	Kuwait (14,154 watts per capita; 168 watts from food)	Iran 4,030 [391 - 14,155] Watts per capita Lowest: Gambia; Highest: Kuwait)	Naha, Japan 3,911 [278.81 - 47,379] Lowest: Montbeliard, France; Highest: Dahka, Bangladesh)	Las Palmas, Spain 12,716,652 [579,030 - 149,754,304] Lowest: NayPyiTaw, Myanmar; Highest: Sinuiju, NorthKorea)

Figure 2. Scaling density as a function of per capita energy use (watts) comparing (A) land mammals, hunter-gatherers, preindustrial societies, and modern cities. (B) A zoomed in plot of cities shows Latin America compared to worldwide. See text for data sources and details.

Energy flux of modern cities far exceeds ecosystems and previous societies

In additional insight from energy use scaling comes from multiplying densities and individual energy use ($E_i \cdot D_{max}$), providing us with an estimate of population-level energy flux, E_p . Theory predicts E_p to be ‘invariant’ or constant over species varying in per capita energy requirements with a slope $\beta = 0$.

$$E_p \propto E_i^0 \quad (4)$$

Plotting the data this way (Fig 3) allows us to compare the E_p across mammals, hunter-gatherers, preindustrial, and modern cities in reference to Net Primary Productivity (NPP) – the rate solar energy is stored in green plant biomass on Earth forming the essential energetic bases of all consumers in food webs in all ecosystems (Fig 3) including humans.

As expected from fundamental limits to ecosystem energetics, the energy flux of mammal populations and hunter-gatherers is ~2 orders of magnitude below the reference NPP. With each transfer of energy, most is lost as heat. Preindustrial societies fluxed greater E_p than other mammals and hunter-gatherers, but did not exceed the ecological ‘green ceiling’ of NPP. This increase is likely due to technological and cultural advancements in plant and animal domestication and food storage during good times (Hammond et al. 2015). In contrast, modern cities flux two orders of magnitude greater energy than background ecosystem levels in NPP through the incorporation of vast quantities of extra-metabolic energy use largely in the form of fossil fuels (Burger et al. 2017). This clearly imposes a major challenge for sustainability. Modern cities must currently subsidize the concentrated local demands of hyper-dense citizens by resources far from outside the urban boundaries (Rees and Wackernagel 2008; Burger et al. 2012; Burger et al. 2017; Burger et al. 2019a, Meyfroidt et al. 2010). This requires vast infrastructure networks in the form of roads, shipping, air transportation (Hammond et al. 2015) and the communication and regulatory networks to coordinate market activity. All of which increase the material, energetic and informational needs per capita, leading to a greater “footprint” (Reese and Wackernagel 2008, Global Footprint Network) and threatening the biophysical capacity of the biosphere.

Figure 3: Population energy flux (E_p) as a function of individual energy use (E_i) for (A) human populations and other land mammals with global average terrestrial NPP as a reference (503,558.48 watts/km²; Haberl et al. 2007). (B) Zoomed in comparison of global cities to Latin American cities and the USA and Canada.

The global trend – where higher per capita energy use countries have higher E_p – is exhibited similarly in Latin American Countries. This includes Caracas in Venezuela – a high energy producing country – as well as different cities within the region’s most developed countries, such as Antofagasta, Chile; Buenos Aires, Argentina; and Mexico City. In contrast, cities in lower energy use countries such as Lima, Peru or Bogota, Colombia flux lower or similar energy as other more developed countries while acquiring greater population densities. However, none of these cities could support themselves from energy and food from local NPP and currently rely on unsustainable global trade networks dependent on fossil fuels (Burger et al. 2012, Schramski et al. 2019).

There are key insights that can be gained from the data: Antofagasta, Chile, stands as the city with the greatest population energy flux ($\sim 38,000,000$ watts/km²), significantly higher than the country's capital (Santiago de Chile, $\sim 15,000,000$ watts/km²). Antofagasta is a port city based on mining and shipping activities, and is an example of how economic activities might be masking the energy flux trends seen for Latin American countries, as these raw materials are exported to global trade markets. It's high density and energy flux could also be due to the constraints on human settlement in the largely inhospitable Atacama Desert. However, even this key economic Latin American city fluxes considerably less energy per area than Sinuiju, North Korea ($150,000,000$ watts/km²), the city with the highest population energy flux in the data. Sinuiju is key for economic activities in North Korea, as the country's main port to China and important for key wood and recycling industries. Finer data and analysis of how energy is allocated by different cities is needed to understand whether the energetic costs actually benefit the urban dwellers, or is it lost to global economic trade activities.

Urbanization trends across and within countries

We can further evaluate the role of energy use in urbanization across decades. Urbanization is a hallmark of the Anthropocene and corresponds with the Great Acceleration – the synchronized surge in a range of measurable human activity including global resource extraction, CO₂ emission, and GDP growth (Steffen et al. 2015; Schramski et al. 2020). The world's population crossed the urban transition around 2010, where > 50% of the world's population lives in cities. However, Europe, Oceania, the Caribbean, USA, Canada and many Latin American countries have been mostly urban for decades prior to 2010 (Fig 4). Indeed, the Latin American countries of Uruguay, Argentina, Chile, Brazil, and Venezuela are more urban than the USA and Canada. On the other hand, the Central American countries of Nicaragua, Honduras and Guatemala have only recently made the 50% urban transition. The rest of Latin American countries transitioned decades before and are generally much more urban than global variation among countries. For example, India with 1.34 Billion people is still mostly rural (only $\sim 35\%$ of its population is urban), while China (with 1.43 billion people) and Singapore (with only 5.61 million) are highly urbanized (60% and 100%, respectively). In Africa, most countries remain predominantly rural (Rwanda 82.8% rural, 12,301,970 people) and few such as South Africa (57.7 million people, 66% urban) are urbanized. Egypt with its nearly 100 million people mostly residing along the Nile river and delta is only 42.7% urban.

Figure 4. The urban transition globally, for select regions and Latin American countries. Data from <http://data.worldbank.org>. Since ~2015 all Latin American countries are predominantly urban. See Burger et al. (2019a) and World Bank for projections to 2050.

Along with urbanization comes increased interdependence of urban populations on rural resources impacting the environment (Rees and Wackernagel 2008; Irwin et al. 2009; Burger et al. 2017; Burger et al. 2012; Burger et al. 2019b; Schramski et al. 2019). Such global trends impose huge pressures on how to subsidize an increasing trend of non-locally energetic sustainable urban centers from other places that seem to lack the technological and/or workforce capacities. Finally, the massive shift of people from rural lands to cities threatens not only the production capacity, but also the resilience of trade networks, as lower income countries are supporting the needs of more high income urban countries (Meyfroidt et al., 2011, Schramski et al. 2019, 2020).

Burger et al. (2019a) analyzed World Bank data among countries and within countries over time showing that per capita GDP, energy use, and CO₂ emissions increased by over two orders of magnitude from low-income, resource-based rural countries to high-income, urbanized countries with service economies. In general, urbanization in Latin American countries is similar (Figure 5 and 6). However, for the level of urbanization, Latin American countries have lower per capita GDP than the world average, translating to lesser energy use and CO₂ production. This income gap could be reflecting differences in economic activities that are developed by Latin American countries compared to the rest of the world, which has historically been affected by their colonization history and the particular raw material and agricultural development that the region has experienced over the past century (Gudynas 2013; ECLAC 2016; Ocampo 2017). Indeed, for the level of urbanization, Latin American countries have greater employment in resource sectors compared to the rest of the world (Figure 6) and much of the national GDP is from resource extraction (Hidalgo et al. 2007; ECLAC 2016), despite being mostly urban societies. Moreover, the World Bank Database defines mining and quarrying activities as “industrial employment”, when are non-renewable resource extraction activities that are sold to other countries as raw material and not processed within the country. Indeed, Latin American countries export vast quantities of raw materials to other countries abroad (Hidalgo et al. 2007, ECLAC 2016), affecting their potential per capita income, as manufactured goods are more lucrative (Hidalgo et al. 2007).

Figure 5. Global trends in per capita values with urbanization across and within countries over time. Data from Worldbank.org with the following countries and political entities removed as outliers: Macao; Hong Kong; and Kuwait. Fitted lines represent LOESS spline fits. Modified from (Burger et al. 2019a) to highlight Latin American countries (red), Canada and USA (blue).

Figure 6. The combined employment (men and women based on Worldbank.org bigender classification) for countries over time. Resource employment includes the total number of individuals employed in resource-extraction occupations such as agriculture, hunting, forestry, and fishing. Industrial employment includes mining and quarrying, oil and gas production, manufacturing, construction, and public utilities such as water, electricity, and gas. Today, most of Latin American economies are dominated by the service sector including wholesale and retail trade, hotels and restaurants, transportation, storage, communications, finance, insurance, real estate, business services, health care, education, recreation, and community, social, and personal services. Guatemala and Honduras are the two Latin American countries that most recently crossed the 50% urban transition in just the last decade. Fitted lines represent LOESS spline fit to data. Highlighted are Latin American countries (red), Canada and USA (blue).

Challenges for sustaining urban resource flows

As shown, extra-metabolic energy use has enabled modern societies to temporarily escape ecological constraints in hyper-dense cities of today. However, the footprint of modern cities – the area and resources required to support an urban population and economy – clearly extends well beyond the local urban boundaries (Rees and Wackernagel 2008; Burger et al. 2012). When considering the sustainability of a particular city, it is important to understand the resource flows – both metabolic and extra-metabolic energy – required to sustain a hyper-dense population. This is akin to ecological footprint (Rees and Wackernagel 2008; Meyfroidt et al. 2011, Burger et al. 2012), which highlights the importance of importing resources far from the urban boundary through fossil fuel-powered global trade networks to sustain localized urban populations (Hammond et al. 2015). The question is how can we sustain hyper-dense cities – and their connections through global trade networks – in a post-fossil fuel world?

One area of increasing interest in Latin America and globally is urban agriculture. But the capacity for urban farms to produce the food demands of modern cities is very low ranging from <1% of caloric demand to 20% under very optimistic scenarios (Grewal and Grewal 2012; Day and Hall 2016; Schramski et al. 2019; Schramski et al. 2020). Moreover, the increasing presence of wild and domesticated animals in dense urban areas poses health risks as global pandemics are known to come from spillover zoonotics in dense urban areas (Kapan et al. 2006; Bradley and Altizer 2007; Wu et al. 2017; Di Marco et al. 2020). Thus, urban food production as a solution to less energy-intensive food security is questionable (Schramski et al. 2020). Other solutions deal with the transition toward renewable energies, but both biophysical (Schramski et al. 2015; Hall and Klitgaard 2018) and innovation rates (Strumsky et al. 2010, Weinberger et al. 2017; Burger 2018) put limits to these alternatives. Moreover, it has amply been shown that energy efficiency does not necessarily lead to more sustainable societal outcomes, as societies with greater energy availability, usually achieved through technological development, tend to increase their per capita demand instead of diminishing it, a trend known as “Jevons Paradox” and/or “Rebound effect” (Alcott 2005; Gralla et al. 2017). The future of cities is uncertain. Pandemics, social instability and environmental impact may result in an exodus from cities and a reversal to resource-employment in local scale farming, hunting, fishing, collecting (e.g., Day et al. 2016). However, it is important to note that the inevitable long-term de-urbanization may not take the same path down as the trajectory up, a concept in complex systems known as hysteresis (Burger et al. 2019b).

Why do Latin American countries have lower economic development for urbanization?

Our results show Latin American countries, for their level of urbanization, have relatively low per capita GDP and energy use; and because these two metrics are so tightly related (Brown et al. 2011, 2014), we would expect that such differences translate into differences in quality of living for the region. Only Argentina, Uruguay and Chile are currently considered as “Very developed” status, according to the HDI, and these countries have higher urbanization rates than the USA and Canada (Fig 4). Interestingly, these are the countries of temperate Latin America, which supports the long observation in economic geography that the temperate zones typically have higher rates of per capita income (Bonds et al. 2012), but also the lack of a proper index for properly quantifying well-being (e.g. GPI). One hypothesis to explain this “Latitudinal gradient in income” is that the ecology of infectious disease drives poverty traps and impacts human distribution, density, and economies (Bonds et al. 2012; Burger and Fristoe 2018; Tallavaara et al. 2018), but also, that we are still lacking of a more international-based index that accounts for environmental impacts of economic trade activities. Certainly, studying the Americas holistically from a human macroecological approach, accounting for their economic activities, provides an excellent opportunity to study the environmental and geographic relations to economic development and options to mitigate through policy and technology.

Economic development in Latin America has historically been based on resources as commodities (ECLAC 2016, Ocampo 2017), that is, the extraction of great amounts of raw materials, such as minerals, oil, wood, foodstuffs, etc., for exportation to international commercial markets. Thus, the region is characterized by urbanization, yet a great dependence on vast natural resource exploitation for exportation for economic growth (i.e. “extractivist economies”, *sensu* Gudynas 2013) and not from industrialization, service, and technology jobs that we see with urbanization in the highest development countries (Pérez 2010, Burger et al. 2019). Indeed, the current social and economic difficulties seen in the region suggests that the benefits of energy use of their countries are not necessarily resulting in greater quality of life for all of their citizens. Countries’ dependence on extractive activities are known to threaten local ecosystems, local communities and economic growth (Max-Neef 1991, Hidalgo et al., 2012, Gudynas 2013), therefore, citizens’ well-being. A more detailed analysis between energetic use, lifestyles, inequality, policy, and economic trade activities for this region is undoubtedly needed.

Finally, knowing that Latin American economies depend on extractive economies, CO₂ emissions for the region are likely severely underestimated. The Worldbank.org database only

reflects emissions that refer to "those stemming from the burning of fossil fuels and the manufacturing of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring". Therefore, it does not include CO₂ emissions as a result of deforestation and land use change. Rapid deforestation, especially in tropical forests, is releasing large quantities of CO₂ that are not accounted for in these estimates. The rate of deforestation in Latin American forests is increasing and represents 25% of all forest loss globally, with fastest rates in Amazonas of Brazil, but increasingly in forests of Colombia, Venezuela, Ecuador and Central America (Curtis et al. 2018). Moreover, it was demonstrated that 87% of all forest loss in the region was mainly due to commodity-driven deforestation with activities that pertain to agriculture, cattle, mining and energy infrastructure (Curtis et al. 2018). Latin American economies mainly depend on natural resource trade, yet there is a great underestimation in the land clearing effects on CO₂ emissions in the region. It is likely Latin American countries have greater CO₂ productions from deforestation activities for their level of urbanization and energy consumption, that is not reflected in our analyses or the Worldbank.org data. We suggest future data compilations to include a complete accounting of CO₂ emissions. These data are essential for delivering the science required for sustainable solutions.

Conclusions

Latin America is following the same urbanization trajectories as global trends, albeit with lower levels of per capita GDP, CO₂ and energy use. The region's trajectory, following common global trends in energy use, poses major challenges for sustainability at local to global scales. Our results clearly show that modern rates of urbanization and the hyper-dense cities now the norm throughout the Americas, is largely dependent on fossil fuels and other resource extraction. They are clearly unsustainable. Alternatives to economic growth paradigms and urbanization should be necessary to uncover a sustainable vision within biophysical limits. A rapid cultural transition to a steady-state human system that acknowledges other development paradigms and/or indexes of quality of living is of the essence.

Our human macroecological approach illustrates the utility of using large-scale data and energetic principles to understand the emergence and future sustainability of cities. Fundamental biophysical and ecological constraints are useful macro-indicators of the ecological sustainability of human systems (e.g., Burger et al. 2012; Brown et al. 2014; Burger et al. 2017; Schramski et al. 2015; Hall and Klitgaard 2018). We suggest these indicators of strong sustainability rather than economic indicators of human capital (Ayres et al. 2001),

because there is no substitute for the current energy basis that powers the economy. A rapid cultural evolution (Nekola et al. 2013; Burger 2018) is needed for society, not based on a fallacy of infinite growth in a finite system (Malthus 1798; Burger 2020), but on improving human well-being (correctly weighting economic, social and environmental factors) within global biophysical constraints and considering future generations.

A productive way forward is to acknowledge these biophysical constraints and enact policy incentives to transition society to levels within biocapacities of regions, while accounting for impacts made by technology and trades. Latin American is rich in natural resources. A recent global analysis of global priority regions for biodiversity, water, and carbon highlighted the importance of parts of Latin America including Mesoamerica, the Caribbean, Valdivian forests of southern Chile, and tropical mountain regions including the eastern slope of the Andes (Jung et al. 2020). Yet, preserving these resources in perpetuity requires a rapid cultural evolution and paradigm shift to policies prioritizing steady-state healthy populations (especially in the tropics), economies within regional biocapacities and lifestyles and technology that couple humans to the biophysical limits of Earth.

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