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Exploring the potentialities of emergy accounting in studying the limits to growth of urban systems

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ABSTRACT

Cities are important urban productive systems whose main goal could be considered the supply of innovation to generate economic growth. However, as well as all social organization managed by scale economies, cities eventually tend to reduce or even stop growth. In this scenario, public policies are essential to avoid the potential collapse of society. The sustainability of cities has been studied through different methodological approaches, but few scientific works assessed the limits of their growth. This paper explores the potentialities of emergy accounting in contributing to the discussions about the limits of growth for urban productive systems. The cities of Araraquara, Bragança Paulista, Campinas, São Paulo and Taubaté were considered as case study due to their socio-economic importance in São Paulo State, Brazil. The time period ranges from 1999 to 2011. Results from the dynamics of "empower" (in seJ/yr) indicate that all assessed cities have the same development pattern, and differences are related to their current development degree. All assessed cities showed an efficiency increase estimated by the conversion of input materials and energy (measured in seJ) into outputs of goods and services (measured in $). However, a stabilization of efficiency was not observed along the studied period. This result suggests that the hypothesized limits to growth do not exist, were not reached, or even the time period considered was not long enough to allow for observing a stabilization pattern. The methodological approach used in this work contributes to assess urban productive systems through a macro-perspective approach using an input-output model of systems functioning.

1. Introduction

The increasing population in urban centers presents opportunities and challenges in the search for sustainable development. For Bettencourt et al. (2007), cities provide economies of scale and optimum conditions of infrastructure, making affordable the access to social services as education, health care, culture and governance. On the other hand, urban systems cause changes in land use, with the increase slums and heat islands. Although providing both solutions and problems, the importance of urban systems – from now on considered as synonymous of urban cities or even simply cities – can be interpreted as related to its functions as the main driver of innovation, economic growth, creativity, power, and richness (Bettencourt and West, 2010).

Cities and all others social organizations driven by economies of scale have a tendency to reduce or even stop their growth (Bettencourt et al., 2007; Odum and Odum, 2001; Tainter, 1995); among others, this issue is discussed by the pioneer book "Limits to Growth" (Meadows et al., 1972). Bettencourt et al. (2007) argued that to maintain cities growing requires innovation to guarantee cities' dynamics during periods of richness and generation of knowledge. This growth strategy based on continuous innovation may slow down a potential collapse because cities hardly will growth indefinitely, which claims for a limit to growth. During this pulsing behavior including growth and degrowth, Odum and Odum (2001) suggest that appropriate long term public policies must be elaborated and applied to avoid that inevitable periods of non-growth result in damages to society.

Although recognizing an increasing acceptance by scientists and policy makers that urban systems display an inevitable pulse between growth and degrowth – similar to the prey-predator model in which food or energy availability supports growth and food or energy scarcity implies degrowth –, few and dispersed information are available regarding "when" the climax of the pulse curve is or will be reached. According to Ji (2015), ecological mod-

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eling can be used by decision makers towards a strategic societal development. One of the most important ecological models, the pulse model, which includes the stages of sharp growth, climax, descent and low resource restoration, can be used to represent global economy (Odum and Odum, 2001). Considering Beijing economy as case study and applying system ecology modeling as methodology, Ji (2015) stated that urban economy, as an open system depending on flows of energy from its neighboring areas, might pulse and its quantitative growth is limited by the finite natural ecosystem. Thus, adjusting urban growth according to surrounding conditions can be considered as an important approach towards sustainable development.

Considering that society is fossil fuel dependent, some energy analysts believe that climax for urban systems will be reached when worldwide fossil fuel reserves become scarce resulting in a drop for the energy return on investment (EROI) index (Hall et al., 2014; Lambert et al., 2014). Other researchers tried to assess climax by linking the pulse curve with the environmental load imposed by urban systems. Investigating the relationship between economy, energy production and consumption, and the air emissions for the Chinese economy from 2000 to 2011, Hu et al. (2014) found that the economic growth demanded fast increase of energy production and consumption (mainly derived from fossil-based energy) and, consequently, an increase in the amount of SO_2, NO_x, and PM_{10} released into the atmosphere. Asici (2013), studying economic growth and its relationship with environmental impacts, found a positive relationship between income and pressure on natural environment. Results from a sample of 213 countries, assuming pressure on nature as released CO_2, mineral, energy and forest depletion, shown that economic growth is dependent on the biosphere's biocapacity, which has physical limits in supplying resources and treating waste. Similar results were found by Tan et al. (2014) when correlating gross domestic product (GDP) with CO_2 emissions and energy consumption in Singapore. These authors shed doubts about the possibility of environmental sustainability going hand in hand with economic growth, because the later leads to more consumption and thereby to more pressure on natural environment.

Trying to answer why increasing and massive spending on research and development (R&D) has not returned a global GDP growth to the levels of 1950–1970, Beaudreau and Lightfoot (2015) stated that R&D alone is not able to restore growth rates to 4–6% per year, because innovation is limited by physical conditions and energy availability. Moreover, in the same way as maximum energy efficiency is limited according to thermodynamic conditions, the area used by a system is also limited. Zhang et al. (2009) found that the increasing investment on education and R&D by the Chinese government between 1991 and 2009 was not able to reduce the environmental impacts (expressed by airborne emissions) associated to the economic growth.

Amongst globally recognized active organizations, the Sustainable Cities Institute (www.sustainablecitiesinstitute.org) made available information regarding what cities have been done towards sustainability. Most of this information is based on local actions and strongly focused on local specificities to identify issues on different aspects, such as energy, water, sanitation, education, health care, public and private transportation, and alternative ways to overcome these issues. It becomes evident that sustainability research is mainly focused on human needs based upon the human receiver side view approach. Although recognized as important aspects to be considered in policies focused on short to medium term, the suggested propositions are frequently locally specific, which difficult application in different cities and regions. There is a need for a long-term strategic planning regarding cities development, which claims for methods and indicators expressing the cities' limits to growth. Indicators are essential in supporting reflections about the optimal efficiency of cities' functioning. Methods and indicators based on holistic perspectives could have some advantage over those with a reductionist viewpoint, because cities are open systems that depend on external resources of energy and matter. In this sense, emergy accounting (Odum, 1996) appears as a powerful alternative among others scientific methodological approaches available in the literature. According to Odum (1996), emergy accounting is able to show which environmental management practices maximize economic vigor through lesser trial and error and may help society to improve efficiency – by creating and innovating – through lesser faults and adapting to changes more rapidly.

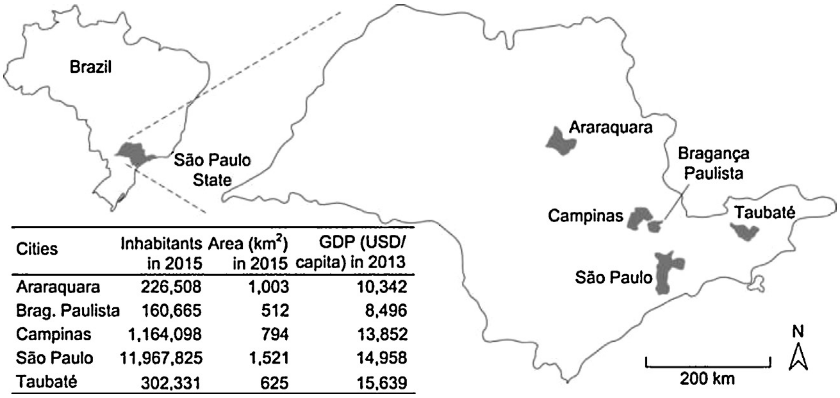
Emergy is defined as the available energy of one kind of previously used up directly and indirectly to make a service or product (Odum, 1996). The emergy accounting method, based on a donor side perspective, presents the energy quality concept by suggesting the existence of an energy hierarch within the biosphere. This concept allows accounting for economic and natural resources – usually considered free-of-charge – on the same basis. Assuming the premise in which the development of cities follow the same development principles of natural systems, it can be argued that cities develop under the principle of maximum "empower" (empower is defined as the flow of emergy per time). This principle, suggested by Odum (1996) as the fourth law of thermodynamics, foresees that "in the competition among self-organizing systems, network designs that maximize empower will prevail". This concept is further discussed by Ulgiati et al. (2007) who argued that systems adapt to environmental conditions through optimizing and not necessarily maximizing their efficiency. Systems adapt to the most appropriate efficiency according to the surrounding environment that supplies resources. Thus, cities are self-organized systems aiming to optimize their efficiency in the conversion of input energy into output of goods and services.

Recognizing that resource availability for system usage is limited and efficiency has a thermodynamic limit, this work aims to provide new insights on the cities limits of growth using the emergy accounting perspective. For this purpose, five cities localized within the State of São Paulo, Brazil, were considered due to their economic and social representativeness.

2. Methods

2.1. Main characteristics of the studied cities

Five cities located at São Paulo State, Brazil, were considered as case studies due to their socio-economic importance for Brazilian society (Fig. 1). They were chosen also due to data availability, however, efforts are suggested for future works in considering greater number of cities and longer time period for simulation than 1999–2011. Fig. 1 shows that studied cities possess different characteristics for number of resident population, territorial area and gross domestic product (GDP). São Paulo city has the largest number for inhabitants, total area, but it has the second position in GDP per capita, while Bragança Paulista is the city with lower number of inhabitants, a reduced total area, and lower GDP. Other characteristics are: (i) Araraquara city is supported by industrial and agricultural sectors, it has a human development index (HDI) of 0.81, annual temperature average of 21.7 °C, and a *Koppen* climatic classification of Tropical wet and dry (Aw); (ii) The economy of Bragança Paulista depends on services than industries, it has an HDI of 0.77, annual temperature average of 19.8 °C, and a Humid Tropical climate (Cwa); (iii) Campinas has a strong industrial sector based in metallurgical processes and concentrates universities and research centers well recognized by their quality, it has a HDI of 0.80, 21.4 °C, and a Cwa climate; (iv) São Paulo is the Brazilian financial center, it also has a diversity of industries and provides



Cities	Inhabitants in 2015	Area (km^2) in 2015	GDP (USD/capita) in 2013
Araraquara	226,508	1,003	10,342
Brag. Paulista	160,665	512	8,496
Campinas	1,164,098	794	13,852
São Paulo	11,967,825	1,521	14,958
Taubaté	302,331	625	15,639

Fig. 1. Localization and main characteristics of five cities considered as case study.

Fig. 2. Representation of the input-state-output model for urban systems. Adapted from Bastianoni et al. (2014).

different services, it has a HDI of 0.80, 20.7 °C, and Cwa climate; (v) finally, the economy of Taubaté city is based on metallurgical and high-tech industries specialized in automobiles and aircraft, it has an HDI of 0.80, 21.7 °C, and Cwa climate.

2.2. Model for ecosystem functioning

According to Pulselli et al. (2011), since the beginning of using thermodynamic approaches to explain how ecosystems work, special attention has being given to the cause-effect binomial that includes system inputs, state and outputs (Fig. 2). Ecosystems are, in fact, open systems where energy and matter cross their boundaries to perform and maintain their functions aiming to maximize the conversion of system inputs into useful goods and services outputs. This model analysis (input-state-output) can be applied to different natural and human-made systems, such as cities. Detailing and studying the "state" of a system (i.e. its internal relationships that drive the maximization of inputs into outputs) is important when the focus is verifying where internal improvements can be applied to help the decision makers and public policies formulations. The model also allows verifying the biophysical limits of growth under a large-scale perspective, and all attentions are directed to "inputs" and "outputs".

Regarding the "inputs", it is recognized the importance of resources quantity and quality as key elements for system development. Thus, environmental accounting using emergy (Odum, 1996) rather than other biophysical approaches is important because it has a systemic characteristic and considers a donor-side perspective, which allows it to recognize the quality of energy; moreover emergy accounting is suggested as a robust methodology (Giannetti et al., 2013). Pulselli et al. (2011) argue that using emergy synthesis to account for system "input" can represent the biophysical counterpart of the "output", i.e. emergy synthesis is able to quantify the environmental work (or real wealth) needed to support human activities in reaching the desirable societal well-being.

Regarding the "outputs", Bastianoni et al. (2014) argue that the larger economy functioning is based on resources conversion into goods and services useful to society, and that their cumulative market value within a society and time period can be represented by their Gross Domestic Product (GDP). Recognizing the GDP's importance and representativeness on the development of an economic system, the GDP is considered in this work as measure of "output" for the proposed conceptual model (Fig. 2).

For both, "inputs" and "outputs", the indicators consider the population size and express per capita values. It is understood that cities exist to allow the people living together and their development, thus, the population number directly acts on the amount of system "inputs" and "outputs".

2.3. Environmental accounting using emergy

Odum (1996; Chapter 10) provides the main variables that should be taken into account when doing an emergy assessment of States and Nations. This traditional approach provides a detailed diagnosis and helps planning towards a more sustainable system by, for instance, replacing or reducing the use of internal and external resources. Several examples of applying emergy synthesis for States and Nations under a traditional approach can be found in literature, as the works of Ascione et al. (2009), Pulselli et al. (2008), Hossaini and Hewage (2013), and Sevegnani (2013).

Although supporting the emergy practitioners in studying these systems, the obtainment of the variables suggested by the traditional approach may turn into a difficult task due to the lack of trustable and complete statistical databases; especially in the Brazilian case. Trying to overcome this operational obstacle in applying emergy accounting, this work considers a macro-perspective approach for gathering raw data. The macro-perspective approach may provide important information about the system operation under a big-picture facilitating dynamic evaluations, time series assessments and long-term planning.

Although considering all the complexity in an energy diagram of a city (including several external energy sources, internal relationships, and a high diversity of goods and services produced), after detailed evaluation and understanding, the complexity can be reduced as represented by the simplified diagram shown in Fig. 3. Usually, there are two external energy sources, one contributing with natural renewable resources ("R") and other contributing with resources from the larger economy ("F"); additionally, there is an internal storage of local non-renewable resource ("N"). These three resources interact within the system boundaries to generate goods and services. The sum of "R", "N", and "F" flows represent the total emergy demanded by system. GDP is generated exclusively by the binomial consumption-production between exportation (output) and "F" inputs; this results in a cyclical behavior between the evaluated system and the broader economy. The natural energy resources "R" and "N" are disregarded by the GDP calculation. For

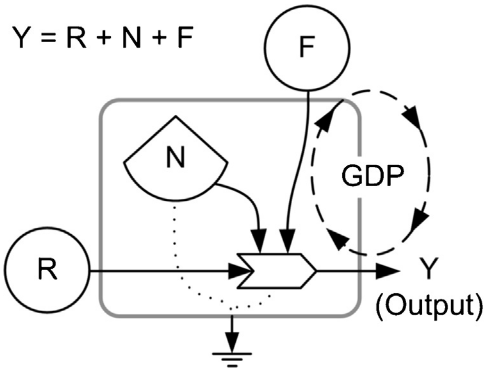


Fig. 3. Generic energy diagram showing the main three energy sources driving a system. Dashed line means currency circulation to generate GDP. Legend: "R" = renewable resources from nature; "N" = non-renewable resources from nature; "F" = resources from economy; "Y" = total emergy demanded by system.

further information on meaning, definition, rules and applications please refer mainly to Odum (1996) and Brown and Ulgiati (2004).

As presented, this work accounts for "R", "N", and "F" emergy flows under a macro-perspective approach considering the time-period of 1999–2011 for the following five cities located in Brazil: Araraquara, Bragança Paulista, Campinas, São Paulo and Taubaté. The next subsections presents details on calculation procedures for each emergy flow.

2.3.1. Renewable resources from nature (R)

The renewable resources "R" considered by emergy synthesis in assessing urban systems are solar radiation, wind, geothermal Earth heat, and rainfall (see, for instance, the works of Hossaini and Hewage (2013), Odum (1996), Sevegnani (2013), Pulselli et al. (2008), Zhang et al. (2009), and Ascione et al. (2009)). Depending on the system development stage, the planning adopted for its developing and its locality, other "R" resources can be found. In accordance with the emergy algebra method, as all "R" resources come from the same energy sources driving the biosphere (solar radiation, tidal energy, and deep Earth heat), the total emergy demanded by any system must include exclusively the highest flow of renewable emergy to avoid double accounting. According with a large number of published works which applied emergy accounting to assess urban systems (see, for instance, the same ones above quoted), usually the "R" flow that deserves highest attention due to its higher emergy is the rainfall, which is considered as representative of "R" resources for the urban systems evaluated.

Differently from natural and agricultural systems in which rainfall is admittedly important mainly to allow photosynthesis and biomass growth, the main function of rainfall in cities can be interpreted as the thermal transfer by reducing cities' air temperature through convection (in the air) and conduction (in the buildings). This different approach for calculating the rainfall transformity is different than considering the chemical potential and physical energy as proposed and used by Odum (1996); although chemical and physical rainfall energy have their importance on cities in the greenery areas and to wash the surface dirty. Thus, thermal energy is considered in this work to calculate the rainfall transformity and then used to assess urban systems under the emergy perspective. As a first calculation attempt, the following heat transfer model is considered for this new approach:

$$Q = m * c * \Delta T \tag{1}$$

Where: Q = thermic heat transferred in J/yr; m = average value for rainfall on Earth, 1.05E17 kg/yr from Odum (1996); c = water specific heat, 4.18E3 J/kg °C; ΔT = increase temperature gradient of water after heat transfer in °C.

A global average value for ΔT was not, at this moment, found in the literature, thus it was assumed a range from 0.1 °C to 5.0 °C based on common sense and on unpublished data, thus potential uncertainties in its value is recognized. After simulating the Q = m*c*ΔT model by considering the above mentioned values, an average value for "Q" is obtained and used to calculate the rainfall transformity: Rainfall transformity in seJ/J = Global emergy budget of 15.2E24 seJ/yr from (Brown and Ulgiati, 2010)/median value for "Q" in J/yr.

2.3.2. Non-renewable resources from nature (N)

When evaluating urban systems through emergy synthesis, usually the non-renewable resource considered is the soil loss, but other "N" resources can be included depending on the system planning and development stage and local conditions. In this work, soil loss is calculated by considering urban areas (impermeable soil due to urbanization) and rural areas (land occupied with native vegetation and agricultural production) from 1999 to 2011. For the rural area, a value for soil loss of 11.9 ton/ha/yr (from Agostinho et al., 2010) is associated with the average soil loss for sugarcane crop that occupies the largest agricultural areas in São Paulo State; more accurate values could be obtained by considering different land uses (and its dynamics along time) for cities rural areas, and using the Universal Soil Loss Equation together with Geographical Information Systems technology. For urban areas, it is assumed that impermeable areas no longer fulfill their basic function of food producer – this same approach is considered by the Ecological Footprint method proposed by Wackernagel and Rees (1996) –, thus the superficial 15 cm of soil layer which contains organic matter, together with impermeable area, are considered in the estimating of annual soil loss volume. The average soil density of 1200 kg/m^3 is considered in the calculation.

2.3.3. Resources from economy (F)

Usually, the resources from economy "F" (named as feedback from economy in emergy nomenclature) can be considered as the main input resources when studying urban systems due to their high dependence on external resource. As previously discussed, Odum (1996; Chap.10) provides a list of the main raw data needed for an emergy analysis of States or Nations, including resources from nature and economy. Among others, resources from economy include the gross national product or total income, fuel and electricity consumption, and the money circulating through imports and exports. All evaluated cities in this work depend on fossil-fuel and external electricity, which usually are the major contributors to the total "F" resources consumption. However, when analyzing the other inputs from economy it is possible to characterize each city according to its main function: Araraquara depends on fertilizers usage for agricultural production; Bragança Paulista on the services provided by other cities; Campinas, Taubaté and São Paulo are quite similar and mainly depend on steel imports for industries, food imports, and services.

When evaluating countries, the way in which "F" resources are usually counted could become a difficult and time-consuming task due to a need for high amount of data, however, it becomes an easy task because statistical database for countries can be readily found. On the other hand, when reducing the systems boundaries as for regions, states, and cities, the availability of primary data becomes scarce – when existent –, which makes difficult the application of emergy accounting. This is especially true for the Brazilian case, in which there is a lack of high quality database for raw data regarding resource demand and production for systems with political boundaries smaller than the national one.

As described by Odum (1996. pg.76), an alternative approach to estimate the "F" resources that enter a city is the use of nomograms relating the density of development (GDP in $/area) with the

Table 1
Dynamics for total rainfall[a] (in $m^3/m^2/yr$) and rainfall emergy[b] ("R", in E14 seJ/capita/yr) for the five studied cities.

Year	Araraquara		Bragança Paulista		Campinas		São Paulo		Taubaté	
	Total rainfall	"R"	Total rainfall	"R"	Total rainfall	"R"	Total rainfall	"R"	Total rainfall	"R"
1999	1.53	6.35	1.76	5.40	1.80	1.13	1.38	0.15	1.44	2.78
2000	1.60	6.53	1.81	5.44	1.75	1.07	1.46	0.16	1.57	2.97
2001	1.36	5.47	1.65	4.87	1.61	0.97	1.46	0.16	1.14	2.13
2002	1.47	5.77	1.51	4.36	1.48	0.88	1.64	0.18	1.36	2.49
2003	1.45	5.60	1.48	4.20	1.42	0.83	1.09	0.12	1.03	1.86
2004	1.63	6.19	1.76	4.89	1.69	0.98	1.64	0.17	1.62	2.87
2005	1.59	5.92	1.83	4.99	1.78	1.01	1.73	0.18	1.12	1.95
2006	1.35	4.96	1.68	4.49	1.65	0.92	2.01	0.20	1.08	1.84
2007	1.36	4.90	1.57	4.12	1.56	0.86	1.43	0.14	1.08	1.82
2008	1.42	5.05	1.87	4.81	1.80	0.97	1.91	0.19	1.52	2.51
2009	1.91	6.65	2.24	5.67	2.19	1.16	2.21	0.22	1.64	2.66
2010	1.35	4.62	1.86	4.61	1.83	0.95	2.16	0.21	0.66	1.05
2011	1.66	5.59	1.75	4.25	1.79	0.92	1.80	0.17	0.87	1.36

[a] Total rainfall obtained from INPE (2014).

[b] Rainfall emergy = Total rainfall ($m^3/m^2/yr$) * (1000 L/m^3) * density (1 kg/L) * Gibbs free energy (5000 J/kg) * cities area (m^2; Appendix A) * (1/population) * Rainfall transformity from Fig. 4 (14,150 seJ/J). It was assumed that population increase follows the same ratio as for 2010 and 2014 years according to IBGE (2014). The obtained annual increase rates were: Araraquara = 1.74%; Bragança Paulista = 1.90%; Campinas = 1.61%; São Paulo = 1.35%; Taubaté = 1.73%.

imports density ("F" in \$/area). The monogram's original author (Brown, 1980) states that there is a strong relationship between these variables. To update the Brown (1980) nomogram for the studied cities, data of GDP for the year 2008, total land area, and volume of imports (all data from Sweeney et al., 2007) for 24 countries spread in the five continents worldwide were used. This updated nomogram uses the most recent values published by Sweeney et al. (2007) and offers a macro perspective containing average values representing the entire world. Eq. 2 (coefficient of determination R^2 of 0.9717) represents the mathematical model that explains statistically the nomogram's curve. Input variables for area (in km^2), population (in inhabitants), and the emergy per money ratio value (in seJ/USD) are used to estimate the "F" flow for different years according to Eq. 3.

$$ID = 0.2516 * (DD)^{1.0451} \qquad (2)$$

Where: ID = Imports density (imports per area) in USD/km^2 yr; DD = Density of development (GDP per area) in USD/km^2 yr.

$$F = ID * area * (1/inhabitants) * EMR \qquad (3)$$

Where: ID = Imports density (imports per area) in USD/km^2 yr, from Eq. 2; Area = cities' total area in km^2; Inhabitants = cities' total inhabitants; EMR = emergy per money ratio in seJ/USD; seJ/USD = 3.0E41 $e^{(-0.033^{*}year)}$, equation obtained by considering the Brazilian seJ/USD ratio for several years as available in Giannetti et al. (2015a).

3. Results and discussion

3.1. Rainfall transformity and "R" resources

Fig. 4 shows that rainfall transformity calculated by considering the thermal transfer (i.e. the cooling city effect) has a decreasing exponential pattern, in which small changes on the initial temperature gradient result in faster decrease of transformity value. Visually, it can be seen that starting from 2.0 °C for temperature gradient until reaching its maximum value of 5.0 °C, the obtained rainfall transformity has little change compared to the initial curve from 0.0 °C to 2.0 °C. Taking into consideration all transformity values calculated in Fig. 4, the resultant median value is 14,150 seJ/J, a value close to Odum (1996) rainfall transformity considering the potential energy (17,620 seJ/J), but about twice as lower than Odum (1996) rainfall transformity considering the chemical energy (30,574 seJ/J). Recognizing that main function of rainfall falling upon cities is the cooling effect, the median value obtained from Fig. 4 is considered in this work as representative of rainfall transformity.

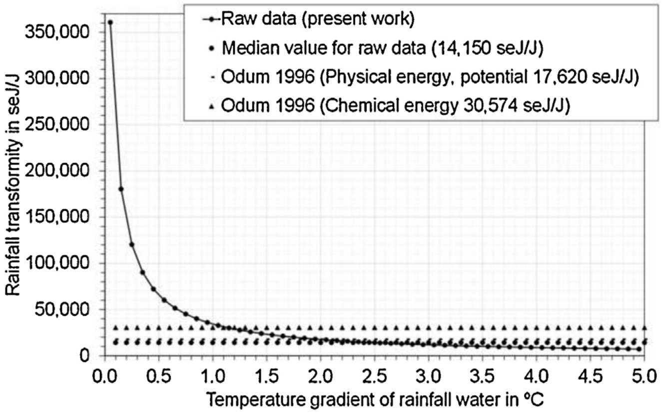


Fig. 4. Rain transformity variation according with water temperature gradient after thermal transfer.

After establishing a value for rainfall transformity for thermal transfer, the total annual rainfall for the five studied cities during the 1999–2011 period was considered in the analyses of the renewable emergy "R" demanded by the urban systems (Table 1). As the rainfall emergy is strongly dependent on rainfall volume falling upon the cities – this is true because all other calculation variables are the same for all studied cities during all the considered period; please see footnote of Table 1–, it becomes evident that a higher amount of total rainfall results in higher emergy from this source, in which the 2009 year showed higher values.

3.2. "N" resources

Appendix A shows the dynamics for non-renewable emergy flow "N" for the five studied cities along with 1999–2011 period. The most representative variables for "N" calculations that express the differences among the urban systems are urban and rural areas, because all other variables are maintained constant – please see footnote of Appendix A. The total area for urban systems remains constant, but the relation between urban and rural areas changes along years due to urbanization processes. Due to restrictions on data availability, this work assumes that increase rate for urban area has the same value as the rate for population growth. Thus, for the year 2011 a highest value for "N" was expected from urban areas compared to previous years, because it was the latest year

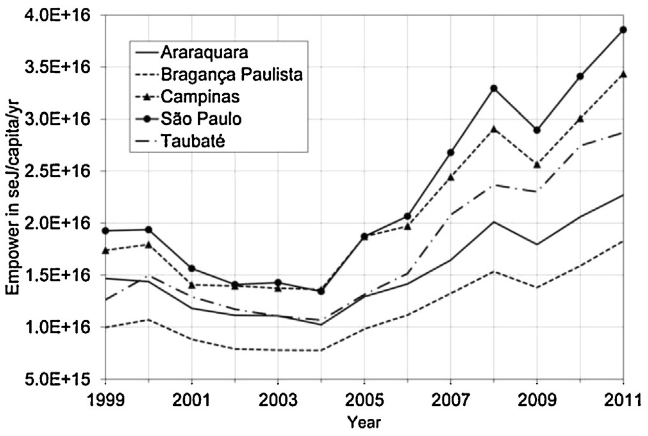


Fig. 5. Empower dynamics for the five studied cities.

considered for the assessed period; and for the year 1999 a lowest value for "N" since it was the first year considered into the evaluation. Although occupying a larger area, the city of São Paulo has a lower demand for "N" resources than all other cities individually, which is explained by the higher number of inhabitants living in São Paulo – all numbers are in per capita basis.

3.3. "F" resources

Appendix B shows that for all the assessed systems there is an increase for "F" demand between years 1999–2000 followed by a decrease between 2001 and 2004, and other increase for 2005–2011. As the calculation procedure for "F" was based on the GDP of assessed cities, the obtained dynamics is a result of the GDP dynamics. Differently of "N" resource in which São Paulo obtained the lower values, now it obtained the highest values for "F" resources among all assessed cities. Although with the largest population – please remind that indicators are in per capita basis –, São Paulo has a huge GDP value compared to other cities, followed by Campinas, Taubaté, Araraquara and Bragança Paulista. Another aspect that deserves attention is that "F" emergy values (seJ/capita year) are about twice as higher than "N" resources, reaching values almost 100 times higher than "R" resources. This indicates that "F" resources have great influence in the total emergy demanded by the urban systems assessed.

3.4. Assessment of limits to growth for the studied urban systems

Fig. 5 indicates that all assessed cities have a similar behavior. They differentiate each other by a certain degree which could be justified by the development stage at which each city finds itself. This argument is valid considering that all assessed urban systems have the same pattern of development, the same policies, and that the relationship between the total input resources (Y) and system output (GDP) are similar; they differ exclusively on scale. Thus, it can be said that all assessed urban systems aims to reach the same development degree of the city that holds the highest empower, which in this work is São Paulo city. Bettencourt et al. (2007) stated, when assessing different cities located in the USA, that although seeming superficially different in form and location, in fact cities are versions of different scales one of the other.

An interesting aspect shown by Fig. 5 is the empower per capita reduction for all assessed cities during 2001–2004. As previously pointed out, the largest emergy demand comes from "F" resources (about twice as much than "N" and 100 times higher than "R"), which makes the reduction of GDP in that period as the main driver of the curveís behavior for Fig. 5. The high currency cambial ratio between USD and BRZ (2.41 BRZ/USD in 2001 and 3.14 BRZ/USD in 2005) can be considered as the main driver for that result, because it reduces the GDP in USD units as considered in this study.

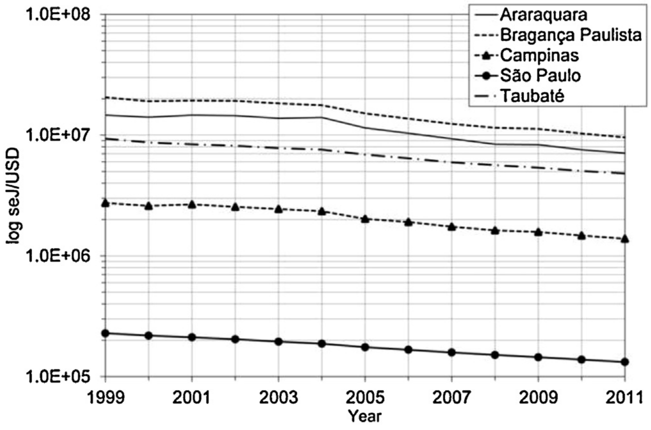


Fig. 6. Dynamics of emergy per money ratio for the five studied cities.

Other important aspect provided by Fig. 5 is the inexistence of a steady state (stabilization) for the empower per capita as initially expected. Thus, by considering the time lag used in the evaluation, it can be said that there is not a limit to growth or that this limit still was not yet achieved by the studied cities. Considering a larger time lag period in the study could result in a different behavior.

Still regarding Fig. 5, it can be observed that the differences among the cities' empower per capita are increasing along years. A possible explanation is that São Paulo citiy, the one with the greatest empower, has already achieved a steady state for its population growth but still has large potential to increase its GDP. The increase in GDP for all other cities occurs through lower ratios than those for population growth; this is a characteristic for those cities located in the outer areas of São Paulo State. For example, for 2002–2005 periods, the city of Campinas holds the same empower per capita than São Paulo. A possible explanation is that Campinas has generated a high amount of GDP due to fast growth of its industries and commerce. However, for the consecutive years, Campinas has experienced a population increase at ratios superior to its economic growth. This resulted in a lower empower per capita for Campinas than São Paulo during the 2006–2011 period.

Fig. 6 indicates that São Paulo could be considered more efficient than all other assessed cities, because it is able to generate more GDP by demanding lower emergy. Considering that all five cities have the same development pattern, Fig. 6 shows that all cities have a tendency to get closer to São Paulo's efficiency. Again, although the dynamics presented by Fig. 6 indicates that all cities are improving their efficiency, a stabilization patterns still cannot be observed, maybe due to the time period considered for evaluation (1999–2011), or even because the pursued stabilization was not yet, or hardly will be, achieved.

Far away from stabilization, Fig. 7 shows an increase for empower per capita directly related with an increase for GDP. It is worth to note that for São Paulo city, high increments of GDP demand low amount of emergy, while for Bragança Paulista and Araraquara cities, low increments of GDP demand high emergy investment. As "R" and "N" resources have low variation among years 1999–2011, thus the GDP for all studied cities is basically dependent on "F" resources. These results are in accordance with Jorgenson and Dietz (2014), in which economic growth leads to those activities that cause high load on environment while not producing proportional increases for human well-being. In this present work, the load on environment is caused in other regions which supply "F" resources to the studied cities. In short, instead of show-

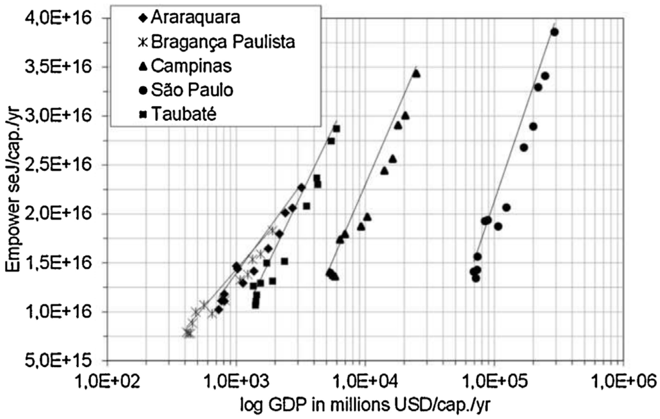


Fig. 7. Dynamics for the relation between empower and GDP for the five studied cities.

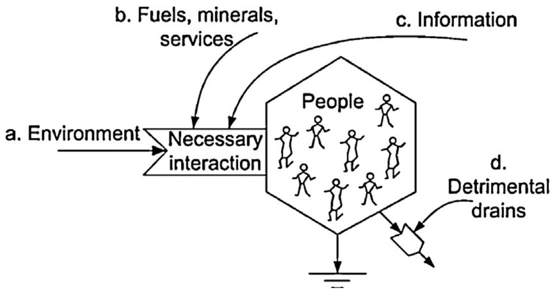


Fig. 8. Emergy requirements for the human well-being including three categories of different transformities (a, b, c).

Source: Odum (1996).

ing a stabilization pattern for emergy demand (input) as initially expected, data show that a city development when measured by its GDP (output) is directly related to emergy demand of “F” resources from external supporting regions.

3.5. Insights about considering the GDP as representative for system output

Using the GDP to represent societal benefits or human well-being as a result of resources demand (emergy in this work) could not be considered the most appropriate, because according to Giannetti et al. (2015b) the GDP is based on the premise that economic growth is always synonymous with better quality of life and it disregards that net profit also depends on natural and social capital, and GDP increase doesn’t guarantee that benefits and/or profits will be distributed to all citizens. This aspect was previously identified by Odum (1996) that, making an analogy with emergy accounting, argues that it could be desirable subtracting all prejudicial drains to human life when calculating the individual emergy index. For instance, the emergy per person lost due to an increase of accidents, crime, pollution, noise, and so on, could be subtracted from individual emergy index. Although seeming simple, Fig. 8 is very enlightening because it is able to exemplify the idea in which societal development depends on resources from natural environment, fuel, minerals, and information, but it is also influenced by the higher or lower amount of prejudicial drains (i.e. negative influences or stress). These drains are responsible by the lost or underutilization of useful emergy.

This Idea is not new even in the economic area. Among others, Daly and Cobb (1989 apud Pulselli et al., 2006 p 272) have proposed a substitute index for the GDP which subtracts the prejudicial drains in the societal development and thus could better represent the economic well-being: Index of Sustainable Economic Well-being (ISEW). It is believed that ISEW provides a more appropriate view of well-being, because it considers some essential aspects as profit distribution, environmental impacts, and loss of environmental quality; in other words, well-being is affected by flow of human services rather than production of marketable goods and services. The ISEW has been used mainly to assess countries (Pulselli et al., 2006; Beça and Santos, 2014; among others), however its applicability can be considered difficult due to a lack of high quality statistical database for countries and also for smaller systems as regions and cities; this operational barrier was also identified by Giannetti et al. (2015b). Specifically for this work, the framework of database considered as supplier for raw data (FINBRA, 2014) is completely different compared to ISEW framework (i.e. ISEW input data doesn’t match with FINBRA 2014 dataset), which makes difficult its application. This operational difficulty in using ISEW framework has been criticized by others authors as in Medeiros et al. (2014). Trying to overcome this issue, an effort was made to identify all functions and subfunctions existent within cities financial accounting (i.e. investments) which could represent the prejudicial drains of well-being as described by ISEW. Unfortunately, due to a lack of deeper details and meanings of existing aspects within financial cities dataset (FINBRA, 2014), it was not possible to make this relationship at this time. Thus, the total GDP was considered as representative for the systems output, however, we recognize that additional efforts must be done aiming to identify and relate all prejudicial drains and subtract them to the total GDP to better express its real contribution to the societal well-being.

4. Conclusions

The obtained rainfall transformity representing thermal transfer (14,150 seJ/J) could be used when applying emergy synthesis in urban systems, because it better represents the real function of rainfall in cities rather than the traditional approaches considering chemical and/or potential rainfall energy.

The obtained similar behavior of empower dynamics for the five studied cities indicates that all of them have the same development pattern, in which the visual differences on graphics indicates the existence of a delay in their current development stage. All cities have shown an improvement in their efficiency by converting input resources (Y) into outputs (GDP) considering the time lag assessed, however, contrary to what was previously expected, the stabilization or steady state for that efficiency was not observed. The lack of evidence for limit to growth in the results suggests that stabilization doesn’t exist, or it still was not reached by the studied cities, or even the time lag considered in this study (1999–2011) was insufficient to observe such stabilization.

Although not pointing to a limit to growth, this work brings important issues as the proposed methodological approach that could be useful when assessing urban systems, including the macro-perspective evaluation (for larger scale studies and aims), the input-output conceptual model (to evaluate efficiency, costs and benefits), and the proposition of rainfall transformity considering thermal transfer (maybe a more appropriate function for cities rather than chemical or potential energy). The next steps suggested to improve this study are (i) to rethink about the use of cooling tower model to replace the used $Q = m^*c^*\Delta T$ model in estimating the rainfall transformity; (ii) extend the time lag for data gathering; (iii) and use the ISEW approach instead of total GDP to better represent the monetary contribution for societal well-being.

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Appendix A.

Dynamics for urban and rural areas[a] (in km^2) and for non-renewable emergy “N”[b] (in E15 seJ/capita/yr) for the five studied cities.

Year	Araraquara			Bragança Paulista			Campinas			São Paulo			Taubaté		
	Urban	Rural	“N”	Urban	Rural	“N”	Urban	Rural	“N”	Urban	Rural	“N”	Urban	Rural	“N”
1999	35.01	973.59	4.16	14.08	500.22	2.53	216.19	581.41	4.20	892.47	636.03	1.60	23.24	604.16	2.04
2000	35.63	972.97	4.15	14.35	499.95	2.52	219.72	577.88	4.20	904.68	623.82	1.60	23.64	603.76	2.04
2001	36.26	972.34	4.13	14.63	499.67	2.51	223.32	574.28	4.20	917.06	611.44	1.60	24.06	603.34	2.03
2002	36.90	971.70	4.12	14.92	499.38	2.50	226.97	570.63	4.20	929.61	598.89	1.60	24.48	602.92	2.03
2003	37.56	971.04	4.11	15.21	499.09	2.49	230.69	566.91	4.20	942.33	586.17	1.60	24.92	602.48	2.02
2004	38.22	970.38	4.10	15.50	498.80	2.48	234.46	563.14	4.19	955.23	573.27	1.60	25.35	602.05	2.02
2005	38.90	969.70	4.09	15.80	498.50	2.47	238.30	559.30	4.19	968.30	560.20	1.59	25.80	601.60	2.01
2006	39.58	969.02	4.08	16.10	498.20	2.46	242.14	555.46	4.19	981.37	547.13	1.59	26.25	601.15	2.01
2007	40.27	968.33	4.07	16.41	497.89	2.45	246.04	551.56	4.19	994.62	533.88	1.59	26.70	600.70	2.00
2008	40.97	967.63	4.06	16.72	497.58	2.44	250.00	547.60	4.18	1,008.05	520.45	1.59	27.16	600.24	2.00
2009	41.68	966.92	4.04	17.04	497.26	2.44	254.02	543.58	4.18	1,021.66	506.84	1.59	27.63	599.77	1.99
2010	42.40	966.20	4.03	17.36	496.94	2.43	258.11	539.49	4.18	1,035.45	493.05	1.59	28.11	599.29	1.99
2011	43.14	965.46	4.02	17.69	496.61	2.42	262.27	535.33	4.18	1,049.43	479.07	1.59	28.60	598.80	1.98

[a] Data for 2005 year were obtained from Miranda et al. (2005). Due to the lack of available information, data for 1999–2004 and 2006–2011 years were estimated by considering that urban area has the same rate of increase than total cities’ population as shown in the footnote of Table 1;

[b] Soil loss emergy = emergy soil loss for urban area + emergy soil loss for rural area; Soil loss emergy for urban area (seJ/yr) = Urban area (m^2/yr) * Soil fertile deep (0.15m) * Soil density (1200 kg/m^3) * Soil organic matter content (4%) * Energy intensity of soil organic matter (5400 kcal/kg; Odum 1996) * 4186 J/kcal * (1/population) * Transformity for soil organic matter (1.06E5 seJ/J; Odum 1996 updated); Soil loss for rural area (seJ/yr) = Rural area (m^2/yr) * Reference for soil loss (1.19 kg/m^2; Agostinho et al. (2010) for sugarcane) * Soil organic matter content (4%) * Energy intensity of soil organic matter (5400 kcal/kg; Odum 1996) * 4186 J/kcal * (1/population) * Transformity for soil organic matter (1,06E5 seJ/J; Odum 1996 updated).

Appendix B.

Dynamics of GDP[a] (in millions USD/capita/yr) and emergy resources from economy “F”[b] (in E15 seJ/capita/yr) for the five studied cities.

Year	Araraquara		Bragança Paulista		Campinas		São Paulo		Taubaté	
	GDP per capita	“F”	GDP per capita	“F”	GDP per capita	“F”	GDP per capita	“F”	GDP per capita	“F”
1999	1,003.84	9.88	485.10	6.90	6,350.14	13.07	84,365.85	17.66	1,351.80	10.30
2000	1,023.16	9.58	561.20	7.63	6,933.15	13.64	88,658.43	17.76	1,723.24	12.63
2001	807.78	7.12	457.35	5.84	5,283.30	9.77	73,919.82	14.02	1,539.74	10.67
2002	769.38	6.43	411.79	4.97	5,482.05	9.67	69,148.76	12.48	1,437.36	9.44
2003	805.49	6.41	425.74	4.88	5,632.39	9.47	73,347.96	12.67	1,418.34	8.85
2004	730.46	5.50	440.62	4.80	5,814.06	9.32	71,756.02	11.82	1,408.27	8.36
2005	1,127.68	8.24	649.45	6.84	9,258.99	14.43	106,913.07	17.11	1,908.61	10.92
2006	1,367.93	9.58	816.82	8.25	10,343.49	15.42	123,831.23	19.04	2,360.70	12.96
2007	1,764.75	11.89	1,069.78	10.38	14,016.66	20.16	169,217.50	25.18	3,502.16	18.61
2008	2,394.86	15.55	1,335.11	12.42	17,902.71	24.79	218,096.31	31.34	4,204.65	21.42
2009	2,155.02	13.24	1,227.83	10.80	16,267.56	21.35	200,064.20	27.33	4,278.12	20.74
2010	2,725.51	16.09	1,541.68	13.00	20,428.87	25.79	246,796.30	32.49	5,441.22	25.35
2011	3,204.55	18.12	1,909.64	15.44	24,819.46	30.09	292,139.64	36.99	5,975.51	26.59

[a] GDP obtained from SEADE (2014) and converted to USD by using the USD/R$ annual average from BACEN (2014).

[b] “F” obtained from Eq. 3.

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