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Accounting for internal stocks in assessing the sustainability of urban systems: The case of ABC Paulista

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ABSTRACT

Environmental assessments of urban systems intend to help city managers to identify feasible measures towards the reduction of urban vulnerability and to the understanding on how cities are dependent on available resources. Through the emergy approach, city managers may recognize subcomponents from each building block that individually and collectively influence the municipalities' environmental performance. Internal stocks of the urban systems play an important role on cities functioning, and the interactions among economic, social and natural capital influence the municipal performance. This paper uses emergy synthesis to account for the internal stocks of the multi-urban system called ABC Paulista, the role of stocks in ABC development and growth. Three forms of capital (economic, social and environmental) were accounted for, which allowed describing the urban settlements according to their nature (such as service provider or industrial cluster). Results may assist policy makers in regard to urban aggregates sustainability and also in formulating policies for particular cities.

1. Introduction

Cities are complex organisms that require different forms of energy such as fossil fuels, water, building materials, food, labor, information, and others. These organisms can be considered points of energy convergence that concentrate energy not only for their maintenance and functioning mechanisms, but also to drive development and growth by stocking assets: houses, industrial buildings, public infrastructure and population.

Urban systems require more energy than that stored within its own boundaries, and either for catabolic and anabolic purposes, inputs of imported energy are often higher than those drawn from local sources implying in a high dependence on the surrounding environment (Lei et al., 2015). Besides the energy withdrawn from other regions, urban centers also generate wastes affecting adjacent areas through direct, secondary, and cumulative impacts (Brown and Vivas, 2005). The urban un-sustainability observed by several assessing methods seems to be an inherent characteristic of urban systems, which cannot grow or develop without subsidy from outside. In a more holistic view, cities can be understood as drivers (or buffers) of the convergence and later divergence of materials and information (Odum et al., 1995). Materials, labor and information from inside and outside the system are combined and processed with the aid of the local stock of knowledge and expertise resulting in products containing a secondary level of information and higher transformity. In a closer look, this mechanism capable of generating higher transformity can be imagined as an industry and the surrounding industries that support its activities. Through time, much of the labor used in this "urban industry" turns into citizens, know-how and expertise.

Several articles have been published for explaining and modeling urban spatial planning and distribution (Su and Fath, 2012; Tehrani and Makhdoum, 2013; Huang, 2005), urban growth patterns and modeling (Van de Voorde et al., 2016; Herold et al., 2005; Weber and Puissant, 2003), urban metabolism (Inostroza, 2014; Kennedy et al., 2014) and urban material flow and resource usage (Piña and Martínez, 2014). In general, all these studies describe and discuss the use of inputs, the fate and the effects of outputs and sometimes yields, using different accounting methods.

Emergy Synthesis (ES) is one of the most comprehensive methods for assessing urban systems. ES allows discriminating among Renewable (R), Non-renewable (N) and Imported (F) resources that

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give support and are combined inside the “urban industry” using local and foreign labor to produce higher quality goods, services and information. In 1995, Odum et al. wrote a report entitled Zonal Organization of Cities and Environment that included a chapter focused on understanding how a low density land use pattern can impact the type and amount of resources consumed by society. Maps of composite land use distribution covering, from 1986 to 1992, were used to follow changes in time of the dominant resources required to support a city (Jacksonville, Florida). ES was also applied to different landscapes in order to create the Landscape Development Intensity, LDI (Brown, 2005; Brown and Vivas, 2005). The LDI was defined as a land use based index of potential human disturbance. LDIs for highly urbanized regions, such as the city of Tallahassee, Florida, were calculated as greater than 8 while LDIs from 1 to 2 corresponded to areas classified as nearly 100% natural lands. Ascione et al. (2007, 2009) applied ES to the city of Rome analyzing the flows exchanged between the city and its surroundings, and the complexity of the internal urban system. Zucaro et al. (2014), applied a combination of ES, Life Cycle Assessment (LCA) and Decomposition Analysis to build a time series of emergy use for Rome. From 1962 until 2008, the empower density rose about 220% and, among of imported resources, the major input was the use of building materials that raised approximately 200% from 1968 to 2008, reflecting the rise in the assets and their maintenance (Brown, 2005).

Recognizing the importance of the maintenance and functioning mechanisms and the role of growing assets in the so called “urban industries”, this paper aims to assess the stocks of three urban systems using ES. For this purpose, a group of three cities with a high dense metropolitan area (Santo André, São Bernardo do Campo and São Caetano do Sul) grouped as ABC Paulista, was chosen as a case study.

2. Method

2.1. System’s description

ABC Paulista is an urban system composed of three municipalities: Santo André, São Bernardo do Campo and São Caetano do Sul, located in the state of São Paulo in the Southeast region of Brazil, and it is also part of the Greater São Paulo that is composed by 40 municipalities including São Paulo (Fig. 1). ABC is an important industrial, technological and housing area that gives support to the Greater São Paulo through major industrial activities related to automotive and chemical sectors. The ABC cities compete for market and local resources, but also share the relative benefits of clustering industrial activities, similar climate conditions, and infrastructure facilities. Table 1 shows main information about the ABC and its municipalities.

Regarding the GDP of 2009, the municipalities of ABC Paulista contributed with 4.8% of the GDP of the state of São Paulo and with almost 3% of the GDP of Brazil in the same year. In Brazil’s GDP rank, São Bernardo do Campo occupied the 13th position and Santo André 29th (IBGE, 2013). The region is also an important supplier of natural resources, as the Billings dam, partially located in Santo André and São Bernardo do Campo is one of the main water reservoirs of Greater São Paulo.

2.2. Emergy synthesis

Odum (1996) defined Emergy as the available energy of one kind previously required directly and indirectly to make a product or service. The use of a common basis (solar equivalent joules, sej) allows the accounting of all energy contributions to obtain a certain product or service.

ES methodology establishes that the resources that support any product, service or system can be divided into indigenous resources renewable, R + non-renewable, (N) and purchased resources (F) that come from outside the system. The total emergy (U) is the sum of R, N, F resources that cross the boundaries from outside the system. In order to account for R, N and F resources in a common basis, the concept of unit emergy values (UEV) relates to the solar emergy necessary to obtain one unit (such as J, g, or currency) of a product or service.

The ABC’s energy system diagram is presented in Fig. 2. The diagram helps understanding the dynamics of the urban ecosystem showing the renewable natural resources (rain, wind and sun) that feed the ABC Paulista (urban areas, agricultural areas, industrial activities), and storages (water reservoirs, standing tree biomass, built environment). The diagram also shows physical components and economic sectors, as well as, their interactions through pathways of matter and energy flows, providing a preliminary picture of internal complexity and dynamics. The Billings dam is partially located at Santo Andre and São Bernardo do Campo supplying water to various municipalities in the region of Greater São Paulo. The municipalities use resources from outside their borders (F) that are shown in the upper part of the diagram (water, fuel, electricity, machinery, products and services). Financial transactions among municipalities and foreign markets are shown on the right side of the diagram.

Industrial and manufacturing activities use the built environment and all items that cross the system’s boundary, yielding products and services that are exported to other locations outside the system. All these activities generate a stock of capital that is represented within the studied system.

2.3. Data collection

ES was performed based on the National Environmental Accounting Database tables (NEAD, 2000), as described by Sweeney et al. (2007). The energy of renewable, imported and exported resources were calculated with data obtained from governmental institutions websites and the city council (IBGE, 2013; CRESESB, 2010; SECEX, 2012; SEADE, 2012; City council of Santo André, 2011; City council of São Bernardo do Campo, 2011; City council of São Caetano do Sul, 2011). The UEVs taken from the literature, using the approximate planetary baseline of 15.83×10^{24} sej/year (Odum et al., 2000). Services that come from inside Brazil were calculated using the Shift-Share analysis better detailed in Sevegnani, 2013. Data from the Foreign Commerce Secretary (SECEX, 2012) were used to calculate the imports from outside Brazil. Labor that comes from other municipalities of the state of São Paulo was calculated combining data of Census 2010 published by IBGE (2013). Labor emergy flows were associated with workers that daily come from the surrounding municipalities to ABC. Further information and details on the ES of the ABC Paulista are available at Sevegnani (2013); Sevegnani et al. (2013), Sevegnani et al. (2015a), Sevegnani et al. (2015b).

2.4. Procedure for stock calculation

Stocks hold a “capital” that can be accounted in emergy terms and in monetary terms. Stocks were divided into three categories: Economic Capital (building and fleet); Natural Capital (water from Billings dam and biomass) and Social Capital (population). Further details on stocks calculation can be found in the Appendix A.

Building stock: The constructed area was calculated by observing the urban zonal map of each municipality. The number of building floors was multiplied by the area to obtain the total constructed area. The total constructed area was multiplied by the emergy per area (4.86×10^{15} sej/m^2) of a regular standard con-

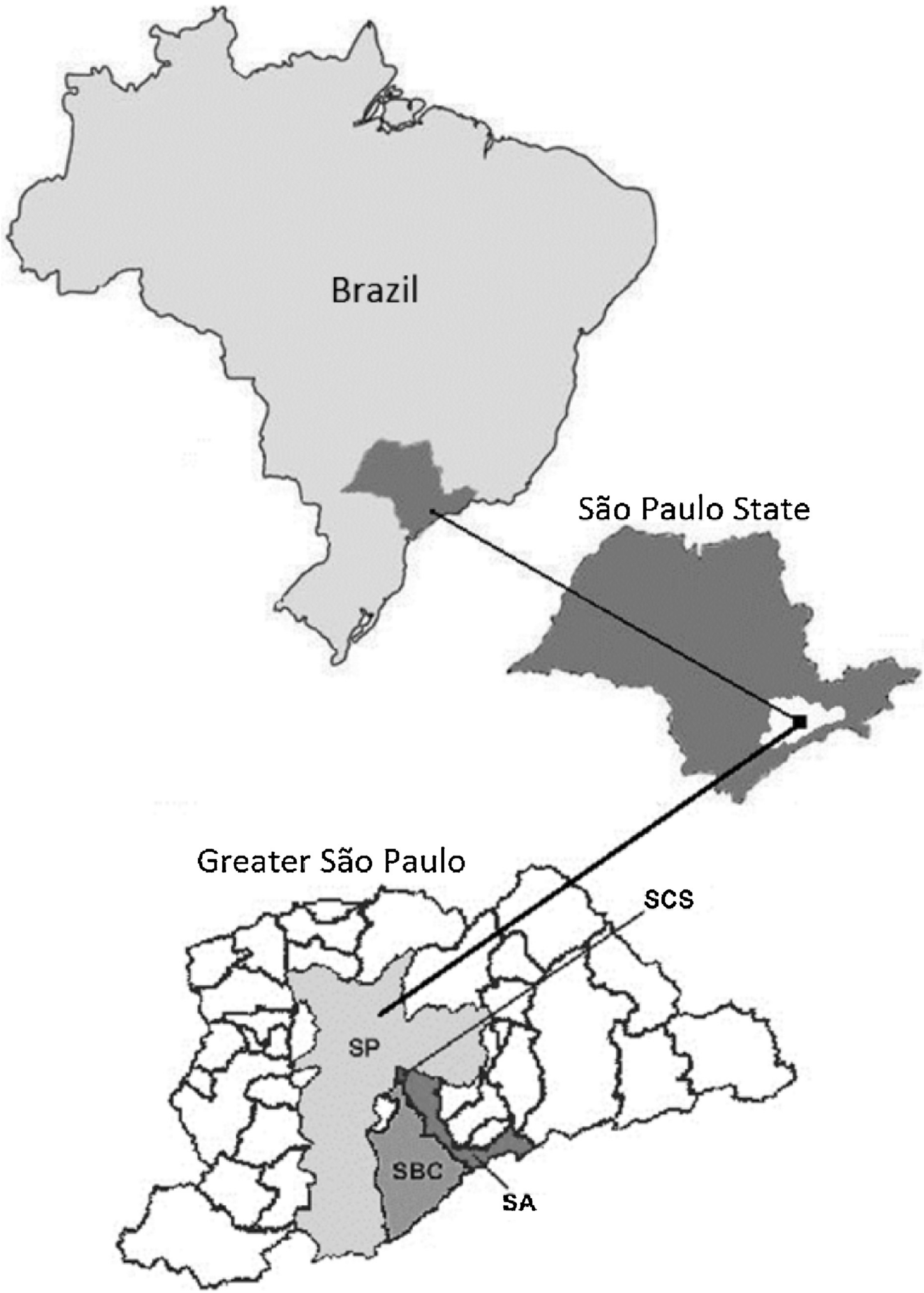

Fig. 1. Location of ABC Paulista in Greater São Paulo, state of São Paulo, and Brazil. Where: SP marks the city of São Paulo, SA Santo André, SBC São Bernardo do Campo and SCS São Caetano do Sul.

Table 1
Main information about Santo André, São Bernardo do Campo, São Caetano do Sul and ABC Paulista.

	ABC Paulista	Municipality		
		Santo André	São Bernardo do Campo	São Caetano do Sul
Area[a] (km^2)	596	175	406	15
Population[a] (inhabit.)	1,636,468	673,396	810,979	152,093
GDP [a] (10^3 USD)	26,282,785	7,354,801	14,467,883	4,460,101
Percentage of green area[b]	42.5	35.8	47.0	0.1
Total in green area (km^2)[b]	253.33	62.62	190.70	0.02

Further information and details on the ES of the ABC Paulista is available at Sevegnani et al. (2013), Sevegnani et al. (2015a) and Sevegnani et al. (2015b).
[a] IBGE (2013).
[b] Secretary of Environment (2009).

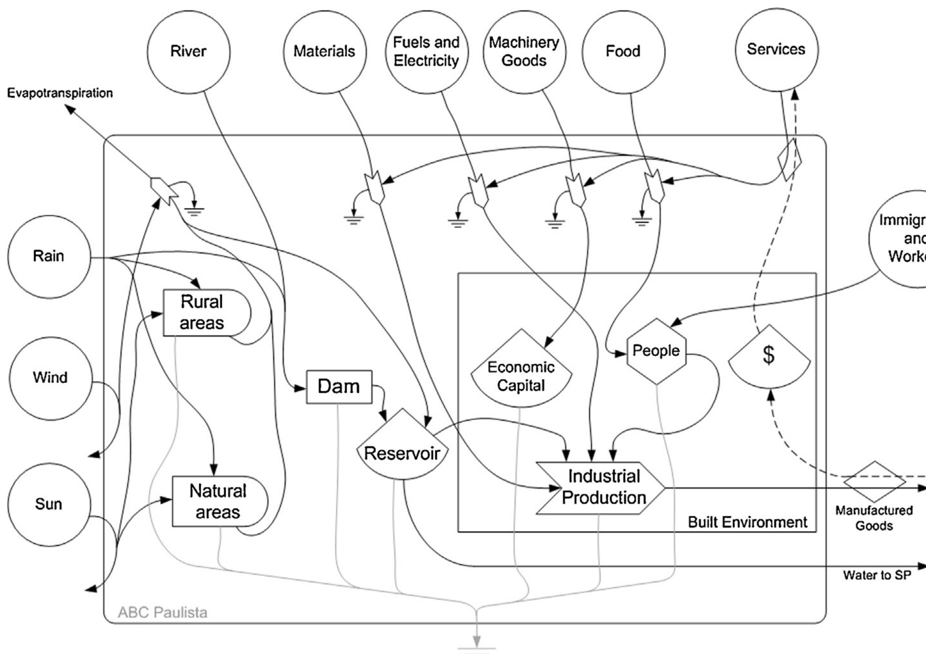

Fig. 2. Energy System's diagram for ABC Paulista.

struction following the Brazilian Standard NBR 12.721/06 and using the data from Demétrio, 2011; resulting the emergy of the building stock.

Vehicle fleet stock: Vehicle fleet was considered as an important stock that demands great quantities of imported resources such as fuels and minerals. Five categories of vehicles were considered: regular cars, trucks, pick-up trucks, motorcycles and scooters. The energy content of materials for each vehicle category was estimated and multiplied by the UEV to obtain the emergy of each vehicle category. The sum of the emergy of each vehicle category resulted the emergy of the fleet stock.

Water stock from Billings Dam: The area of Billings dam inside each municipality was calculated and the percentage of the total area was calculated and multiplied by the total volume of dam, obtaining the volume of water inside each municipality. The energy content of the total volume was multiplied by its transformity (4.10×10^4 sej/J, Odum, 1996) resulting the emergy of the water stock in each municipaility.

Biomass stock: Two types of vegetation were identified in the municipalities, forest and Capoeira (secondary forest). The energy of each type of vegetation was calculated as the area multiplied by the net primary production (NPP). The energy was multiplied by the transformity to obtain the emergy and then by the turnover time (100 years for the forest and 5 years for the capoeira) resulting the emergy of biomass stock.

Population stock: The population stock was calculated considering the quantity of inhabitants in each range of ages of the municipalities. The emergy per capita of each municipality was multiplied by the number of inhabitants inside the range of age and multiplied by the average age of the range resulting the emergy of the inhabitants in that range of ages. Adding all the ranges of ages it is obtained the emergy of the population stock of the municipality.

Once the emergy value of each stock is calculated, values were divided by the Emergy Money Ratio (EMR) of each municipality resulting the emergy-based currency value (Em$) giving an idea of the economic value of the environmental dimension.

3. Results and discussion

The summarized ES evaluation of the ABC Paulista is shown in Table 2. Details and further information were published elsewhere (Sevegnani, 2013; Sevegnani et al., 2013; Sevegnani et al., 2015a; Sevegnani et al., 2015b). The aggregated list of input flows clearly confirms that local flows, renewable or not, are negligible compared to imported emergy flows in all three cities.

Part of the flows discriminated in Table 2 is used in maintaining and producing assets that support the cities' activities and support population welfare. Over time, cities store significant amounts of resources. Materials and energy stored are used to increase the size and complexity of the system, and the accounting of storages may help to understand and to measure the system's complexity. The

Table 2
Emergy flows of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC.

Indicator	Unit	ABC Paulista	Santo André	São Bernardo do Campo	São Caetano do Sul
Renewable emergy flow	sej/year	1.17×10^{20}	2.76×10^{19}	7.98×10^{19}	1.55×10^{18}
Fraction used, local renewable	%	< 0.01	< 0.01	< 0.01	< 0.01
Flow from indigenous non-renewable reserves	sej/year	1.72×10^{17}	2.81×10^{16}	1.44×10^{17}	0
Fraction emergy use derived from indigenous sources	%	0.27	0.21	0.38	0.05
Flow of imported emergy	sej/year	3.69×10^{22}	1.29×10^{22}	2.08×10^{22}	3.22×10^{21}
Fraction of use purchased	%	99.73	99.79	99.62	99.95
Total emergy, U *	sej/year	3.70×10^{22}	1.29×10^{22}	2.09×10^{22}	3.22×10^{21}

Table 3
Emergy of the stocks of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC Paulista.

Category	Stock	Emergy of the stock (sej)			
		ABC Paulista	Santo André	São Bernardo do Campo	São Caetano do Sul
Economic capital	Building	1.31×10^{25}	5.36×10^{24}	7.43×10^{24}	2.56×10^{23}
	Vehicle fleet	8.63×10^{21}	3.67×10^{21}	3.87×10^{21}	1.09×10^{21}
	Car	7.32×10^{21}	3.14×10^{21}	3.26×10^{21}	9.22×10^{20}
	Truck	6.20×10^{20}	2.43×10^{20}	2.99×10^{20}	7.78×10^{19}
	Pick-up truck	6.39×10^{20}	2.64×10^{20}	2.85×10^{20}	9.04×10^{19}
	Motorcycle	3.88×10^{19}	1.75×10^{19}	1.80×10^{19}	3.40×10^{18}
	Scooter	3.93×10^{18}	1.59×10^{18}	1.91×10^{18}	4.34×10^{17}
Natural capital	Water	2.40×10^{20}	1.99×10^{19}	2.20×10^{20}	–
	Biomass	7.13×10^{20}	1.62×10^{20}	5.51×10^{20}	–
	Forest	2.16×10^{20}	3.64×10^{19}	1.80×10^{20}	–
	Capoeira	4.97×10^{20}	1.26×10^{20}	3.71×10^{20}	–
Social capital	Population	1.27×10^{24}	4.49×10^{23}	6.86×10^{23}	1.24×10^{23}

accounting was performed considering three categories of stocks: economic, natural and social (Table 3). Detailed calculations can be found in the Appendix A.

The Economic capital of ABC includes assets such as buildings, machinery, and infrastructure. Natural capital provides many functions including, provision of natural resources such as biomass, water to production and housing activities. Social capital includes human resources mainly. All three forms of capital coexist and interact driving development, growth and complexity, and the emergy of the natural capital corresponds to a measure of the cities' reliance on natural resources. According to the principle of strong sustainability, ecosystem's goods and services cannot be replaced by human-made capital (Giannetti et al., 2015; Frugoli et al., 2015). However, in all three cities, the contribution of ecosystem goods and services represents less than 1% of the total. The relationship between the biomass stock and the total emergy is 5.9 for SA and 6.9 for SBC, indicating that the distribution of natural biomass (forest and capoeira) is similar to both cities.

These results show that the ABC Paulista, as many other urban centers, has developed and grown relying on economic and social capitals, without preserving green areas and local resources. It is also interesting to note that economic capital is greater than the social capital, which indicates that materials and energy imported to support industrial activities overwhelm the contribution of labor and services in these cities. In fact, ABC can be seen as an "urban industry", which transforms raw materials into vehicles and chemicals. This "industry" holds the know-how (information), the infrastructure, which allow contribute to the development of the major system (state or country), but also establishes an extreme dependence on resources and environmental services that may come from outside its borders (Sevegnani, 2013; Sevegnani et al., 2015a). Fig. 3 shows the distribution of economic, natural and social capital in ABC Paulista. The contribution of Natural capital is negligible and does not appear in the figure.

In ABC, the major contributors to the value of storages are the built environment (approximately 95%) and the social capital with the remaining 8%. However, two aspects come to attention when the storages are evaluated in separate for each city. The first is that the fleet, despite the great quantity of material used for its construction corresponds to less than 1% of the economic capital. The other aspect is that the social capital of São Caetano do Sul corresponds to 32% of the city's total capital, confirming that export of services is a major characteristic of this city. The relationship among stored capital and the total emergy of each city (Table 4) shows that the empower of the service-based city has the lowest economic capital, indicating that service-based cities attract fluxes of higher transformities than the industrial-based ones. The relationship between the social capital and the total emergy remains practically the same, and that of NC/U is negligible for all three cities.

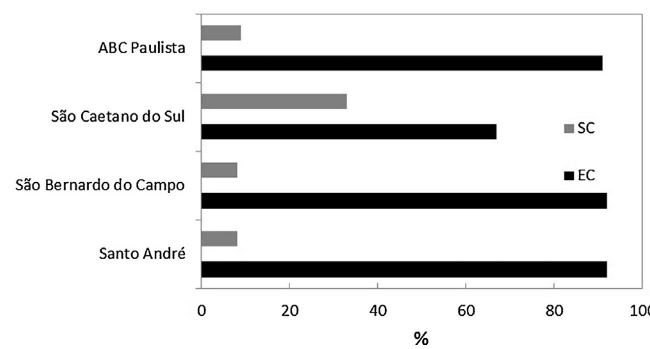

Fig. 3. Distribution of Economic (EC), Natural (NC) and Social (SC) capital in ABC Paulista. NC contribution is insignificant and does not appear in the figure.

The calculated emergy storages (Table 3) were converted into currency values by dividing them by the EMR of each municipality (Table 5). This analysis provides an emergy-based currency equivalent that may provide useful insight into the reliance of economic activity on natural capital and guide the development of effective policies and corporate decisions (Lou and Ulgiati 2013).

The emergy-based currency equivalents shown in Table 5 consent a raw, but useful, quantification of the value of estimated resources in each city. When the emergy of storages is converted into a "emergy-based" currency, the value of a storage may be understood not only based on market underlying forces, but also on the environmental support needed for the gathering and growing

Table 4
Relationship between capital of the stocks (EC, NC and SC) and total emergy (U) for Santo André, São Bernardo do Campo, São Caetano do Sul and ABC Paulista.

	ABC Paulista	Santo André	São Bernardo do Campo	São Caetano do Sul
Economic capital/U	352.8	416.2	355.8	79.8
Natural capital/U	0.03	0.01	0.04	0.00
Social capital/U	34.2	34.8	32.8	38.6
Economic + Natural + Social capital/U	387.1	451.0	388.7	118.4

Table 5
Emergy-based currency equivalent of the storages of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC Paulista.

	Emergy-based currency equivalent/10^{10}(Em$)			
	ABC Paulista	Santo André	São Bernardo do Campo	São Caetano do Sul
Economic capital	837	271	471	29.4
Natural capital	0.061	0.0092	0.049	–
Social capital	81.2	22.7	43.4	14.2
Total	919	294	514	43.6

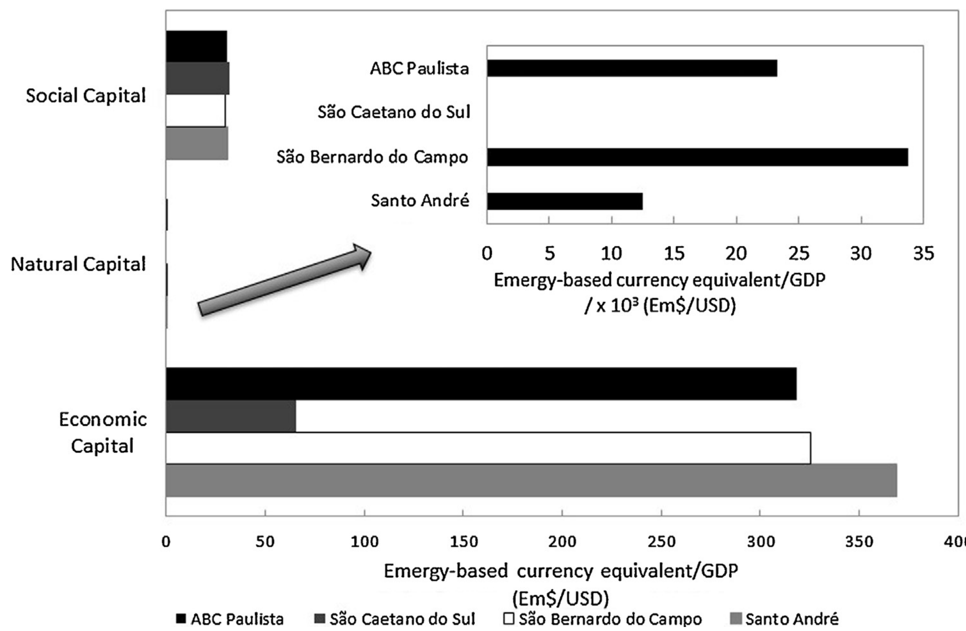

Fig. 4. Emergy-based currency equivalent per GDP of the storages of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC Paulista. In detail the emergy-based currency equivalent per GDP of the natural storages for the three cities and ABC.

of the cities' assets, thus specifying to what degree assets' values are dependent on the environment.

The emergy-based currency equivalent includes the contribution to the cities' assets provided by storages that do not have economic value, and at municipal level, the value of all storages' currency equivalents can be compared to the actual GDP in a given year and show the contribution of storages to produce one unit of GDP (Fig. 4). The bars in Fig. 4 can be interpreted as the capital required to generate one GDP unit, but also as the quantity of capital that is available for a GDP unit in each municipality. It is possible to estimate the loss a municipality would experience if stocks are changed or overexploited (e.g. if the available volume of the dam declines), but it is also possible to appraise the benefits of increasing the biomass stocks.

The analysis shown in Fig. 4 allows characterizing the urban settlements according to their main nature. São Caetano do Sul stands as a service provider, as this city shows high Em$/USD relationship for social capital and 32% of the total emergy stored (Fig. 3), that is, the lowest Em$/USD relationship for economic capital and the highest GDP/inhabitant of about USD 29,000 (Table 1). Santo André and São Bernardo do Campo fit characteristics of industrial clusters, with similar Em$/USD relationship for social capital and 8% of the total emergy stock (Fig. 3). However, Em$/USD relationship for economic capital show that in both municipalities, values of 300 Em$ are required to generate one GDP unit. These results are partially supported by those of Table 6, which shows the relationships between the emergy of the economic and social capitals with the cities' GDPs and their areas.

The relationship between the emergy of the economic stored capital and GDP decreases from Santo André (73×10^{13} sej/USD; 307×10^{20} sej/km^2) to São Bernardo do Campo (51×10^{13} sej/USD; 183×10^{20} sej/km^2). The lowest value belongs to São Caetano do Sul (6×10^{13} sej/USD; 171×10^{20} sej/km^2), where there is also the highest currency flow due its economy based on services with higher aggregated economic value. It is worth of attention that for all three cities the relationship EC/area does not change as function of the economic activity. However, the relationship SC/area changes substantially, while the difference of the relationship SC/GDP does not. The results of ABC are similar to those of São Bernardo do Campo, indicating that the urban settlement, in spite of the intrinsic characteristics of each city, can be represented by this city.

Table 6
Relationship between economic capital, social capital per GDP and economic capital, social capital per area for Santo André, São Bernardo do Campo, São Caetano do Sul and ABC Paulista.

	ABC Paulista	Santo André	São Bernardo do Campo	São Caetano do Sul
Economic capital/GDP $\times 10^{13}$ (sej/USD)	50	73	51	6
Economic capital/area $\times 10^{22}$ (sej/km^2)	2	3	2	2
Social capital/GDP $\times 10^{13}$ (sej/USD)	5	6	5	3
Social capital/area $\times 10^{21}$ (sej/km^2)	2	3	2	8

4. Conclusions

In the case study of ABC Paulista, results confirm that urban systems require much more feedback from the economy than local resources (renewable or not), which if interpreted by traditional emergy indicators would result in non-sustainable systems. However, it was shown that part of the high empower of these cities is used to develop and maintain high quality assets, which give support to activities that produce high transformity goods and services. Materials and energy stored are used to increase the size and complexity of the system, and the accounting of storages may help to understand and to measure the system complexity sheltering know-how and expertise.

The emergy approach provided fundamental understanding by recognizing the existence of deterministic principles in economic systems and the role of resources, energy and environment.

The emergy synthesis of the stocks of ABC Paulista was used as a case study for reflecting on the role of stocks in cities development and growth. The emergy-based currency equivalent of a natural and social capital stocks allowed assessing the ability to support the economic system and the losses related to the degradation brought by misuse. The conversion of emergy values to emergy-based currency equivalents grants the estimation of the contribution of storages to produce one unit of GDP, and potential losses due to stocks changes or overexploitation. Results also permit to value the potential benefits of increasing the natural stocks.

Accounting for the three forms of capital (economic, social and environmental) allowed to characterize the urban settlements according to their main nature (such as service provider or industrial cluster), and may help policy makers not only to address cities' sustainability, but also in formulating policies for particular settlements.

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Appendix A. Stocks calculation

Building stock estimate calculation

The resources used in a standard medium construction were obtained from Demétrio (2012). Calculations are shown in Table A1.

Table A1
Calculation of the emergy per area of a standard medium construction.

Resources	Quantity	Unit/m^2	UEV (sej/unit)	References for UEV	Emergy (sej/m^2)	%(*)
Wood	1.52×10^1	kg	2.40×10^{12}	a	3.65×10^{13}	0.75
Steel/Iron	7.02×10^1	kg	6.97×10^{12}	b	4.89×10^{14}	10.07
Cooper	3.47×10^{-1}	kg	1.04×10^{14}	c	3.61×10^{13}	0.74
Sand	5.78×10^2	kg	1.68×10^{12}	a	9.71×10^{14}	19.98
Ceramic Masonry	3.81×10^2	kg	3.68×10^{12}	b	1.40×10^{15}	28.86
China	5.66×10^1	kg	4.80×10^{12}	b	2.72×10^{14}	5.59
Cement	1.73×10^2	kg	3.04×10^{12}	d	5.26×10^{14}	10.82
Glass	1.37×10^0	kg	1.41×10^{12}	a	1.93×10^{12}	0.04
Plaster	1.34×10^2	kg	3.29×10^{12}	c	4.41×10^{14}	9.07
Granite	2.33×10^2	kg	2.44×10^{12}	c	5.69×10^{14}	11.70
Asphalt	1.23×10^0	kg	2.55×10^{13}	b	3.14×10^{13}	0.65
PVC tubes	4.48×10^{-2}	kg	9.86×10^{12}	b	4.42×10^{11}	0.01
Paint	3.24×10^0	kg	2.55×10^{13}	b	8.26×10^{13}	1.70
Water	6.80×10^2	kg	9.23×10^8	e	6.28×10^{11}	0.01
Total Emergy/m^2					4.86×10^{15}	sej/m^2

a: Odum (1996); b: Brown and Buranakarn (2000); c: Pulselli et al. (2007b); d: Pulselli et al. (2007a); e: Buenfil (2001); planetary baseline of 15.83×10^{24} sej/year (Odum et al., 2000). (*) The percentage column represents the fraction of the emergy of each resource in relation to the total per m^2.

Table A2
Estimate of areas by different use of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC.

	SA	SBC	SCS	ABC
Total area (km^2)	175.00	406.00	15.00	596.00
% of green area	35.78	46.97	0	42.50
Green area (km^2)	62.62	190.70	0	253.31
% of urban area	64.22	53.03	100	57.50
Urban area (km^2)	112.39	215.30	15.00	342.69
% commercial area	34.44	48.86	31.72	24.94
Commercial area (km^2)	38.71	105.20	4.76	148.66
% residential area	65.54	51.14	68.28	32.55
Residential area (km^2)	73.66	110.11	10.24	194.00

The estimate of areas by different use was made by observation of maps found at the city council websites resulting the data shown in Table A2.

See Tables A3 and A4

Table A3
Detailed calculation of the constructed area by type of occupation in Santo André and São Bernardo do Campo.

Type of occupation	Maximum number of floors allowed	% of urban area	Area (km^2)	Constructed area (m^2)(*)
Santo André				
A	2	3.77	4.24	5.93×10^{06}
B	4	30.67	34.47	1.10×10^{08}
C	11	32.89	36.96	3.25×10^{08}
D	16	3.33	3.74	4.79×10^{07}
E	21	21.77	24.47	4.11×10^{08}
F	30	6.00	6.74	1.62×10^{08}
G (no restriction)	30 (considered)	1.55	1.74	4.18×10^{07}
Total constructed area				1.10×10^{9}
São Bernardo do Campo(**)				
A	2	18.86	40.61	5.68×10^{7}
B	4	30.00	64.59	1.81×10^{8}
C	11	25.66	55.25	4.25×10^{8}
D	16	2.60	5.59	6.27×10^{7}
E	21	16.99	36.57	5.38×10^{8}
F	30	4.68	10.08	2.12×10^{8}
G (no restriction)	30 (considered)	1.21	2.60	5.47×10^{7}
Total constructed area				1.53×10^{9}

(*) considering occupation of 70% of the land. Constructed area = Area × number of floors × 0.7. (**) considering the same standard of Santo André, due to the lack of information regarding number of floors.

Table A4
Detailed calculation of the constructed area by type of occupation in São Caetano do Sul.

Type of occupation	Estimate number of floors	% of urban area	Area (km^2)	Constructed area (m^2)(*)
Santo André				
Residential low density	3	34.35	5.15	1.08×10^{7}
Residential low and medium density	8	33.92	5.09	2.85×10^{7}
Commercial area	4	31.72	4.76	1.33×10^{7}
Total constructed area				5.26×10^{7}

(*) considering occupation of 70% of the land. Constructed area = Area × number of floors × 0.7. The total constructed area of each municipality shown in Table A3 and Table A4 was multiplied by the energy per area value (4.86×10^{15} sej/m^2) shown in Table A1: Emergy = constructed area × emergy per area.

Fleet stock calculation

See Tables A5 and A6

Table A5
Calculation of the fleet stock of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC as a whole.

Vehicle type	SA	SBC	SCS	ABC
Regular car	288,100	299,434	84,655	672,189
Emergy of cars (sej)	3.14×10^{21}	3.26×10^{21}	9.22×10^{20}	7.32×10^{21}
Truck	8,359	10,303	2,679	21,341
Emergy of truck (sej)	2.43×10^{20}	2.99×10^{20}	7.78×10^{19}	6.20×10^{20}
Pick-up truck	18,950	20,400	6,478	45,828
Emergy of pick-up truck (sej)	2.64×10^{20}	2.85×10^{20}	9.04×10^{19}	6.39×10^{20}
Motorcycle	45,656	47,004	8,900	101,560
Emergy of motorcycle (sej)	1.75×10^{19}	1.80×10^{19}	3.40×10^{18}	3.88×10^{19}
Scooter	5,530	6,647	1,514	13,691
Emergy of scooter (sej)	1.59×10^{18}	1.91×10^{18}	4.34×10^{17}	3.93×10^{18}

IBGE (2013).

Table A6
Calculation of the emergy of the vehicles that compound the fleet of ABC Paulista.

Material	UEV (sej/kg)(*)	Generic Sedan			Truck			Pickup truck		
		%	Mass (kg)	Emergy (sej)	%	Mass (kg)	Emergy (sej)	%	Mass (kg)	Emergy (sej)
Plastic	9.68×10^{12}	9.3	143.00	1.38×10^{15}	9.3	356.19	3.45×10^{15}	9.3	170.97	1.66×10^{15}
Nonferrous metal (**)	7.76×10^{11}	9.0	138.00	1.07×10^{14}	9.0	344.70	2.67×10^{14}	9.0	165.46	1.28×10^{14}
Metal ferrous (**)	3.16×10^{12}	64.0	985.00	3.11×10^{15}	64.0	2,451.20	7.75×10^{15}	64.0	1,176.58	3.72×10^{15}
Fluids (**)	6.38×10^{11}	4.8	74.00	4.72×10^{13}	4.8	183.84	1.17×10^{14}	4.8	88.24	5.63×10^{13}
Rubber (**)	6.38×10^{11}	6.9	105.00	6.70×10^{13}	6.9	264.27	1.69×10^{14}	6.9	126.85	8.10×10^{13}
Glass	3.50×10^{12}	2.8	42.00	1.47×10^{14}	2.8	107.24	3.75×10^{14}	2.8	51.48	1.80×10^{14}
Other materials (**)	1.34×10^{14}	3.3	45.00	6.03×10^{15}	3.3	126.39	1.69×10^{16}	3.3	60.67	8.13×10^{15}
		Total	1,532.00	1.09×10^{16}	Total	3,830.00	2.91×10^{16}	Total	1,838.4	1.39×10^{16}

Material	UEV (sej/kg)(*)	Motorcycle			Scooter		
		%	Mass (kg)	Emergy (sej)	%	Mass (kg)	Emergy (sej)
Plastic	9.68×10^{12}	6.0	7.20	6.97×10^{13}	6.0	5.40	5.23×10^{13}
Nonferrous metal (**)	7.76×10^{11}	7.0	8.40	6.52×10^{12}	7.0	6.30	4.89×10^{12}
Metal ferrous (**)	3.16×10^{12}	78.0	93.60	2.96×10^{14}	78.0	70.20	2.22×10^{14}
Fluids (**)	6.38×10^{11}	3.0	3.60	2.30×10^{12}	3.0	2.70	1.72×10^{12}
Rubber (**)	6.38×10^{11}	5.0	6.00	3.83×10^{12}	5.0	4.50	2.87×10^{12}
Glass	3.50×10^{12}	1.0	1.20	4.20×10^{12}	1.0	0.90	3.15×1012
Other materials (**)	1.34×10^{14}	0.0	0.00	0.00×10^{0}	0.0	0.00	0.00×10^{0}
		Total	120.00	3.82×10^{14}	Total	90.00	2.87×10^{14}

(*) UEVs: plastic: Brown and Arding (1991); Nonferrous metal, Metal ferrous: Bargigli and Ulgiati (2003); Fluids and Rubber: Brown et al. (1992); Glass: Brown and Ulgiati (2004); Other materials: Odum (1996). (**) Transformity of nonferrous metal was considered the same of aluminum; transformity of metal ferrous was considered the same of steel and iron; transformities of fluids and rubber were considered the same of chemicals; other materials were considered to be textiles. Composition of a generic sedan vehicle (Sullivan et al., 1998). Truck was considered to be 2.5 times heavier than a generic sedan and Pickup truck 20% heavier than a generic sedan, keeping the same percentages of each material. Estimated composition and mass of a regular 125 cc motorcycle. Scooter considered to be 20% lighter than a regular 125 cc motorcycle.

Water stock calculation (Billings dam)

See Tables A7

Table A7
Calculation of the emergy of water stock of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC as a whole.

	SA	SBC	SCS	ABC
Total area (km^2)	175.00	406.00	15.00	596.00
Area of the dam inside the municipality (m^2)(*)	6.85×10^6	7.58×10^7	0	8.27×10^7
Percentage of the dam inside the municipality	5.40	59.79	0	65.20
Volume of the dam inside the municipality (m^3)	6.21×10^7	6.87×10^8	0	7.49×10^8
Mass of water inside the municipality (kg)	6.21×10^{10}	6.87×10^{11}	0	7.49×10^{11}
Energy of water inside the municipality (J)	2.89×10^{14}	3.20×10^{15}	0	3.49×10^{15}
Emergy of water inside the municipality (sej)	1.99×10^{19}	2.20×10^{20}	0	2.40×10^{20}

(*) Area of the dam inside the municipality was calculated by observation of maps found at the city council websites. Area of the dam inside the municipality = Total area of the dam × percentage of the dam inside the municipality Total area of the dam = 1.27×10^8 m^2 (Rocca, 1995). Volume of the dam inside the municipality = Total volume of the dam × percentage of the dam inside the municipality. Total volume of the dam (at full capacity) = 1.27×10^9 m^3 (Rocca, 1995). Mass of water inside the municipality = Volume of the dam inside the municipality × density of water (1,000 kg/m^3). Energy of water inside municipality = Mass of water inside municipality × Gibbs number Gibbs number = 4.66 J/g. Energy of water inside municipality = Energy of water inside municipality × Transformity. Transformity of the water storage = 4.10×10^4 sej/J (Odum, 1996).

Biomass stock calculation

See Tables A8

Table A8
Calculation of the biomass stock of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC as a whole.

	SA	SBC	SCS	ABC
Total area (km^2)	175.00	406.00	15.00	596.00
% of green area	35.78	46.97	0	42.50
Green area (km^2)	62.62	190.70	0	253.31
% of urban area	64.22	53.03	100	57.50
Urban area (km^2)	112.39	215.30	15.00	342.69
% of forest(*)	1.74	3.70	0	3.03
Forest area (km^2)	3.05	15.02	0	18.07
Energy of forest (J/yr)	6.58×10^{13}	3.24×10^{14}	0	3.90×10^{14}
Emergy of forest (sej)	3.64×10^{17}	1.80×10^{18}	0	2.16×10^{18}
Emergy of forest × Turnover Time (sej)	3.64×10^{19}	1.80×10^{20}	0	2.16×10^{20}
% of Capoeira(*), (**)	34.00	43.26	0	39.45
Capoeira area (km^2)	59.50	175.64	0	235.14
Energy of capoeira (J/yr)	1.51×10^{15}	4.44×10^{15}	0	5.95×10^{15}
Emergy of capoeira (sej)	2.51×10^{19}	7.42×10^{19}	0	9.93×10^{19}
Emergy of capoeira × Turnover Time (sej)	1.26×10^{20}	3.71×10^{20}	0	4.97×10^{20}

(*) map of green area (Secretary of Environment, 2009). (**) Capoeira is a type of secondary forest. Energy of forest = green area × net primary production (NPP) of forest. Energy of forest = (______m^2) × (______J/m^2 × yr). NPP of forest = 2.16×10^{07} J/m^2 yr (Lu et al., 2006). Emergy of forest = Energy of forest × Transformity of forest. Transformity of forest = 5.54×10^{03} sej/J (Lu et al., 2006). Emergy of stock of forest = Emergy of forest × Turnover time of forest. Turnover time of forest = 100 yr (estimate). Energy of Capoeira = green area × net primary production (NPP) of Capoeira*. Energy of Capoeira = (______m^2) × (______J/m^2 × yr). NPP of Capoeira = 2.53×10^{07} J/m^2 yr calculated after Siche et al. (2006). Emergy of Capoeira = Energy of Capoeira × Transformity of Capoeira. Transformity of Capoeira = 1.67×10^{04} sej/J (considered the same of Savanna, Brown and Bardi, 2001). Emergy of stock of Capoeira = Emergy of Capoeira × Turnover time of Capoeira. Turnover time of Capoeira = 5 yr (Fearnside, 1996; Skole et al., 1994).

Population stock calculation

See Tables A9

Table A9
Population stock of Santo André, São Bernardo do Campo, São Caetano do Sul and ABC.

Population type	SA		SBC		SCS		ABC	
	Individuals	Emergy (sej)	Individuals	Emergy (sej)	Individuals	Emergy (sej)	Individuals	Emergy (sej)
Incomplete high school	393,174	1.21×10^{22}	465,485	1.43×10^{22}	73,349	2.25×10^{21}	932,008	2.86×10^{22}
Incomplete graduation	186,379	1.64×10^{22}	199,926	1.76×10^{22}	40,621	3.58×10^{21}	426,926	3.76×10^{22}
Complete graduation	96,855	1.96×10^{22}	100,053	2.02×10^{22}	35,294	7.14×10^{21}	232,202	4.70×10^{22}
	Total	4.81×10^{22}	Total	5.21×10^{22}	Total	1.30×10^{22}	Total	1.13×10^{23}
Emergy of the stock		3.37×10^{24}		3.65×10^{24}		9.08×10^{23}		7.92×10^{24}

Range of ages of the population	Average age of the range	SA		SBC		SCS		ABC	
		Inhabitants	Emergy (sej)	Inhabitants	Emergy (sej)	Inhabitants	Emergy (sej)	Inhabitants	Emergy (sej)
0-4yo	2	39,826	1.52×10^{21}	49,373	2.70×10^{21}	6,972	3.01×10^{20}	96,171	4.48×10^{21}
5-9yo	7	41,331	5.52×10^{21}	50,662	9.68×10^{21}	7,295	1.10×10^{21}	99,288	1.62×10^{22}
10-14yo	12	47,831	1.09×10^{22}	58,874	1.93×10^{22}	8,612	2.23×10^{21}	115,317	3.22×10^{22}
15-19yo	17	49,540	1.61×10^{22}	59,739	2.77×10^{22}	9,398	3.45×10^{21}	118,677	4.69×10^{22}
20-24yo	22	57,372	2.41×10^{22}	68,175	4.10×10^{22}	11,091	5.26×10^{21}	136,638	6.99×10^{22}
25-29yo	27	60,821	3.13×10^{22}	72,576	5.35×10^{22}	12,252	7.14×10^{21}	145,649	9.15×10^{22}
30-39yo	35	109,140	7.18×10^{22}	131,592	1.24×10^{23}	22,685	1.69×10^{22}	263,417	2.11×10^{23}
40-49yo	45	99,302	8.43×10^{22}	112,438	1.37×10^{23}	22,550	2.16×10^{22}	234,290	2.43×10^{23}
50-59yo	55	80,252	8.34×10^{22}	84,227	1.25×10^{23}	20,036	2.36×10^{22}	184,515	2.34×10^{23}
60-69yo	65	49,303	6.06×10^{22}	46,488	8.19×10^{22}	13,800	1.92×10^{22}	109,591	1.64×10^{23}
more than 70	75	41,689	5.96×10^{22}	31,269	6.40×10^{22}	14,572	2.36×10^{22}	87,530	1.53×10^{23}
Total	–	676,407	4.49×10^{23}	765,413	6.86×10^{23}	149,263	1.24×10^{23}	1,591,083	1.27×10^{24}

(IBGE, 2013). Emergy per capita of SA = 1.91×10^{16} sej/inhabitant; Emergy per capita of SBC = 2.73×10^{16} sej/inhabitant; Emergy per capita of SCS = 2.16×10^{16} sej/inhabitant; Emergy per capita of ABC = 2.33×10^{16} sej/inhabitant. Emergy of the range of ages = Emergy per capita of the municipality * average of age of the range * number of the inhabitants of the range.

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