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BIOCAPACITY OF BRAZILIAN BIOMES USING EMERGY ECOLOGICAL FOOTPRINT CONCEPTS

Wallan Azevedo dos Santos [I]
Milton Erthal Junior [II]
Renato Gomes Sobral Barcellos [III]

[I] Instituto Federal Fluminense, Mestrado SAEG, Campos dos Goytacazes, Rio de Janeiro, Brasil.

[II] Instituto Federal Fluminense, Mestrado SAEG, Campos dos Goytacazes, Rio de Janeiro, Brasil.

[III] Instituto Federal Fluminense, Mestrado SAEG, Campos dos Goytacazes, Rio de Janeiro, Brasil.

Abstract: This work aimed to assess Brazilian biomes' biocapacity (BC) using concepts of the Emergy Ecological Footprint method. Climate and forest cover data were interpolated using the Kriging method. In 2016, the Brazilian BC was among the largest in the world, 42.11 gha / cap. The biomes' forest coverage areas were investigated and simulated in two scenarios: optimistic (with 100% forest coverage) and pessimistic (only 10%). The Amazon's contribution of half the Brazilian BC would reduce by 88% in a pessimistic scenario. The Atlantic Forest contribution was only 1.9% of the national BC, however, in an optimistic scenario, it would increase by 690%. The reduction of deforestation, fires and expansion of areas protected by law are measures that positively impact the BC of the studied biomes. This methodology can be used as an environmental quality indicator as it adheres to the principles of Sustainable Development.

Keywords: Environmental Management; Emergy; Sustainability Indicators; Sustainable Development.

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Introduction

A balanced development model must be based on multiple levels of sustainability, namely, institutional, cultural, environmental, political and territorial levels (ALVES et al., 2011). One important aspect of environmental sustainability is the value of the natural capital of the ecosystems and their compensation for the environmental services they provide to society (CHAN *et al.*, 2017). Based on the estimation of that value, it is possible to define how the natural capital behaves under the effects of the pollution and degradation of nature and the exploitation of natural resources (energy, water, food, wood etc.) and how the ecosystem services like climate regulation, purification of the air and the waters, maintenance of nutrient cycles, carbon fixation etc., can be jeopardized by anthropic intervention.

One way of assessing the degree of sustainability of the development model for a given location, region or country is to estimate its biocapacity (BC). The BC is the capacity of an area to offer natural resources and assimilate the residues generated by the resident population (WACKERNAGEL et al., 2005), which makes it an interesting parameter for delineating a limit between human activities and the ecosystems (YANG et al., 2018). For that reason, this indicator has many applications in territorial management such as in geopolitical strategy, inter-company competitiveness, government relations and evaluating the population's quality of life (NICCOLUCCI et al., 2012).

In addition to the BC, many countries use other sustainability indicators to subsidize their decision-making processes in regard to territorial management. Such indicators facilitate a better understanding of the data associated to environmental impacts, the general scale of degradation and environmental monitoring (WIEDMAN; BARRETT, 2010). The most commonly used methodologies for those purposes are Net Primary Productivity (NPP) (LIETH, 1973), Ecological Footprint (EF) (WACKERNAGEL; REES, 1996) and Emergetic Analysis (ODUM, 1996). Like the BC, Ecological Footprint can be used to evaluate sustainability levels on different scales that may be individual, processual, institutional or even on the scale of a city or a country (WACKERNAGEL, REES, 1996; GALLI et al., 2016).

EF becomes more efficient for evaluating ecosystem environmental service flows when it is associated with Emergy Analysis (ZHAO et al., 2005; CHEN; CHEN, 2006; SICHE et al., 2008; NAKAJIMA; ORTEGA, 2016). Emergy is a factor of transformity used to correct for externalities of the energy flows involved in products and services production which classical economics does not usually take into account. Emergy-Ecological Footprint (EEF) is a completer and more robust indicator providing a more precise panorama of the level of sustainability in a given location and its ecological reality (Wiedmann & Barrett, 2010).

In their pioneering work on the use of EEF to assess environmental sustainability Zhao et al., (2005) conducted a case study in the Chinese province of Gansu. The study showed that data obtained with conventional EF were underestimated. Chen and Chen (2006) used the same methodology to estimate the level of sustainability of Chinese society's consumption between 1981 and 2001 and, based on EEF, Yang et al. (2018) made a new ecological security proposal for that country. Bagliani et al. (2008) investigated the environmental sustainability of the Italian province of Siena and concluded that the combination of EF with BC enabled a more detailed investigation of the region's environmental aspects. Siche et al. (2008) proposed some improvements to the

EEF measurement methodology and applied their study to various countries.

Pereira and Ortega (2012) were pioneers in using EEF to estimate Brazilian biocapacity and proposing modifications to the method that Zhao et al. (2005) developed. To calculate the BC Pereira and Ortega (2012) included a new category of values to be used in the calculation base namely, 'areas not occupied by humans' and that parameter has been used in the present study. In Brazil, Nakajima and Ortega (2016) employ the Emergetic Analysis to evaluate the support capacity of the Ibiúna region, improving the diagnosis of environmental problems and provide a basis for possible future public policies directed at the conservation of nature.

Regarding the prominent position among ecological creditors on the planet (MARCHI, 2011), Brazil has a significant BC and presents a favorable scenario in the new green economy. The country has a huge territory, geographic diversity, and varied climate and vegetation all of which have led to the formation of different biomes and ecosystems. However, the destruction of native vegetation, the fires, arbitrary land use, and pollution are among the factors that promote a decline in the environmental services that Brazilian biomes provide (Table 1) and consequently in the nation's BC (GONZALEZ; ANDRADE, 2015). Population growth is another cause for concern particularly in view of the lack of conservation planning and practices.

Some initiatives have been carried out endeavoring to monitor and evaluate the level of degradation of the Brazilian biomes such as the 1988 Amazon Deforestation Calculation Program (*Programa de Cálculo do Desflorestamento da Amazônia* -PRODES), the 2004 Real-time Deforestation Detection System (*Sistema de Detecção do Deforestation em Tempo Real* -DETER) and the Brazilian Biomes Environmental Monitoring Program of 2007 (*Programa de Monitoramento Ambiental dos Biomas Brasileiros* - PMABB) (MMA, 2016). Nevertheless, when analyzing data and information in an isolated manner, it is not possible to establish a point of equilibrium between the need for human development and the biome's capacity to support it. Furthermore, it is necessary to plan the occupation of still-preserved areas.

The factors that contribute the most to increasing the BC of natural ecosystems are: rainfall, winds, solar radiation, and the level of vegetation cover (PEREIRA, ORTEGA, 2012; NAKAJIMA, ORTEGA, 2016). The climate and vegetation cover variables may be highly heterogeneous even in different regions of a single biome and consequently have an impact on the BC at the regional level. Studies of this kind with indications of the variations in the data of the biomes (Amazon, Cerrado, Atlantic Forest, Caatinga, Pampas, Pantanal and the Coastal-Marine System) need to be formulated to subsidize the occupation of the territory and the sustainable use of its natural resources. Considering the high rate of deforestation observed in those biomes in recent years, it can be inferred that human intervention is having a negative impact on Brazil's national EF and BC. Those are the issues that have motivated the present research.

Thus, the object of this work is to calculate the biocapacity of the Brazilian biomes based on the concepts underlying the Emergetic-Ecological Footprint method (EEF), with georeferenced data and software to calculate the interpolation of the data and present the results in map form. To evaluate the relationship between the degree of deforestation of the biomes and their BCs, three situations were simulated. One was realistic, based on the 2016 data (the most recent data available at the time the study modelling was conceived), one was optimistic (100% forest vegetation coverage), and one was pessimistic (10% of forest vegetation cover).

Methodology

The study methodology was based on the EEF method for evaluating the BCs of the Brazilian biomes with adaptations to enable the performance of a more detailed analysis of the impacts on the biomes stemming from human actions. Briefly, the methodology was structured in six stages: a) characterization of the case study; b) data gathering from official databases; c) using Geographic Information Systems to process the climate data and elaborate the maps; d) calculation of the EEF and BC; e) simulation of extreme scenarios; and f) sensitivity analysis.

a) Study object characterization

The Brazilian BC was estimated for the year 2016 because at the time of the elaboration of the mathematical modelling it was the most recent year for which data was available to operate the model with. Brazil is an outstanding country in many of the parameters that are important for the planet's environmental accounts. With a territorial area of 8,514,876.599 km^2 and more than 6,700,000 km^2 of marine/coastal zone, it occupies 47% of South America and is the world's fifth largest country (IBGE, 2019). With 14% of the entire world biota, the country has greatest biodiversity on the planet and it was the first signatory to the Convention on Biological Diversity (CBD) (GODINHO; DA MOTA, 2013). Brazilian territory is currently considered to have seven biomes, namely, Amazon, Cerrado, Atlantic Forest, Pantanal, Pampas, Caatinga and the Coastal-Marine system (MMA, 2016; IBGE, 2019). Because of their megadiversity, endemism and the destruction of their natural areas, the Atlantic Forest and the Cerrado are classified as World Hotspots, that is to say, among the areas with the richest biodiversity but at the same time among the planet's most threatened areas (NUNES CARVALHO et al., 2010). Table 1 displays the total areas, areas of standing forest, protected areas and main threats to the Brazilian biomes

b) Data Gathering

The data needed to estimate the BC of the Brazilian territory were obtained from databases of official reports of government bodies and NGOs. The Brazilian Geography and Statistics Institute's (IBGE) database for 2016 was accessed to obtain demo-geographic information such as territorial area, population figures and urbanized areas dimensions. In that year the Brazilian population was 206,081,432 inhabitants, the fifth largest population in the world. The biome delimitations were obtained from the IBGE (2019). To estimate the world population and the BC of the spaces not occupied by humans, the study consulted the World Bank (2016) and CIA (2016) respectively. The sources for the information on preserved vegetation in the biomes were the MMA (2016) and SOS MA (2016). Information on climate variations (insolation, rainfall and winds) was obtained from the reports of the Brazilian government entities CRESESB (2000, 2012) and INPE (2011) and the geographic locations of the meteorological stations, from the INMET (2011). The Emergy Society Database was used to obtain transformity values and the global emergy density. The analytical procedures this study employs were based on the scientific articles of Odum (1996, 2000), Pereira and Ortega (2012) and Zhao et al. (2005).

Table 1 – Original area, preserved area, protected areas and main threats to the seven Brazilian biomes

Biomes	Area (km^2)	Remaining stands of forest vegetation (%)	Area in PAs (%)	Main threats
Amazon	4,230,490	81.0	27.7	Deforestation and burning Mining Large scale crop and livestock production Installation of big public works such as hydroelectric plants
Cerrado	2,047,146	54.5	8.6	Deforestation Livestock production in pasture Agriculture
Atlantic Forest	1,059,027	12.5	10.1	Overuse of natural resources Disorderly urbanization Fauna and Flora extinction risks Irregular land occupation
Caatinga	825,750	54.4	7.6	Deforestation Overgrazing Fauna and Flora extinction risks
Pampas	178,243	46.0	2.7	Desertification Overgrazing Introduction of exotic species Irregular land occupation
Pantanal	151,186	85.0	4.6	Hydroelectric plant installations Nutrient leaching Silting Sewage discharge Sugarcane cultivation
Coastal-Marine System	6,700,000	-	-	Introduction of exotic species Deforestation of mangrove swamps and restingas Itinerant agriculture Crop and livestock farming Disorderly urbanization Sewage discharge

Source: elaborated by the authors, 2018.

Legend: PA = Protected Area. Sources: Adapted from CERRI et al., 2007; SAWYER, 2009; PILLAR et al., 2009; NUNES CARVALHO et al., 2010; ALMEIDA, 2016; UBIRAJARA et al., 2016; RÊGO et al., 2018.

c) Interpolation calculation and Map production

In alignment with the methodology employed by other authors (MELLINO et al., 2015; SUN et al., 2015; YANG et al., 2018; ZHOU et al., 2009) this study used a Computer Assisted Software called Surfer (Golden Software, Inc.) to insert the values of the climate variables wind, solar radiation and rainfall and the georeferencing data

Using the 141 georeferenced points corresponding to the INMET (2016) meteorological stations, windspeed, rainfall and insolation values were attributed to each point. The points were grouped according to the territorial limits of the biomes and the meteorological stations within those limits. After the values for each parameter of interest had been determined for each point, they were interpolated using the Kriging method. Based on the calculations, a map of biocapacity iso-values was produced to facilitate visualization of the variation of the values and the constructed iso-value lines. Kriging is a geo-statistical interpolation and auto-correlation method whereby data for a limited number of points can be used to parameterize the estimations of unshown points which gives it an advantage over other methods (SANTOS et al., 2016) d

The purpose of using interpolation is to facilitate the contrasting of extreme values and the identification of the greater and smaller anomalous values and how the variation between those points occurs spatially. Kriging is an inverse distancing interpolation method with a weighting system whereby the value of a node in the points network is weighted on the basis of the sum of the points that lie within a zone of influence. The similarity of the values is greater when the distance separating the points of interpolation is smaller. Similarity diminishes up to a certain distance at which the values lose all similarity (HENGL, 2009).

Determining those points made it possible to estimate the values in an electronic spreadsheet in which the necessary calculations were performed to define Emergy Flow and BC. It must be underscored that because the number of representative points for the entire vast national territory is very small, even if the values were represented directly at those points, it would still not be possible to obtain a more consistent assessment of the spatial variations in the values and therefore it is necessary to use an interpolation method that highlights the anomalies. In the case of the visualizations via maps, that makes the contrasts among biomes more perceptible to the map reader.

Renewable resources such as the chemical potential of rain (INPE, 2011), solar radiation (CRESESB, 2000) and wind (CRESESB, 2012) that are annually received by the seven Brazilian biomes including the Coastal-marine zone were estimated based on equations 1, 2 and 3 (PEREIRA and ORTEGA, 2012). The climate data were obtained from the databases of entities such as the INPE and the CRESESB.

$$\text{Solar Energy (J)} = As \times Im \times (1 - Al) \times F \qquad \text{Equation 1}$$

Where As = the area of the respective space in m^2; Im= Average insolation in kWh/m^2.year; Al = Albedo; F= the Factor to convert Joules to kWh, namely, 3.60 x E+06.

$$\text{The Chemical Potential Energy of rain (J)} = As \times P \times \rho H2O \times Wqp \qquad \text{Equation 2}$$

Where, P = Rainfall in m/year; $\rho H2O$ = Water density in kg/ m^3; Wqp= Chemical potential energy of water J/kg.

Wind energy (J) = As x ρAr x C x Vm x 3,14E+07 (s/year) Equation 3

Where, C = Drag Coefficient; ρAr = Air density in kg/m^3; Vm= Average wind velocity in m/s.

d) Biocapacity

The division of the Brazilian territory into its seven biomes, including the coastal zone, was the first step for estimating the BC. In view of the diversity of ecosystems and climate of each national biome it was necessary to gather representative data for the spaces under study so that the results could express the variations expected in the biomes themselves.

In addition to the biomes, the study considered the categories 'urban areas' and 'global areas not occupied by humans'. Even though the global uninhabited areas do not contribute expressively to BC accounting when conventional methodology is used, they were considered proportionally to the territory being studied. Deserts, glaciers and oceans are considered to be the 'areas not occupied by humans'. The methodological aspects in this stage of the study were based on the article of Pereira and Ortega (2012) with the necessary updating of the areas based on CIA (2016). The BC estimates for these areas differ somewhat from those of previous work. Given that such areas are globally shared spaces, the value obtained for the emergy flow in their case was divided by the world population and not by the population of the specific region under analysis.

Next the renewable energy flows that occur in each space were calculated using equations 1, 2 and 3. The calculated energy flows were converted into emergetic energy flows (seJ/year) (Equation 4) based on the transformity factors for each type of renewable energy taken from the Emergy Database (2017) and from Odum (2000).

Emergy (seJ/ano) = E x T Equation 4

Where, E= Available energy in J/year; T= Transformity in seJ/J. The base units of solar energy are Joules of solar energy equivalent (seJ). The transformity factor presents a relation of the proportionality between energy and Emergy which is defined as the quantity of Emergy needed to generate a unit of energy of the other type that is, Emergy/unit of energy (seJ/J). The transformity of a product is calculated by adding up the emergy inputs to the process and dividing the total by the energy aggregated to the product. The greater the quantity of energy transformations needed to obtain a product or execute a process the greater the value of the transformity will be (ODUM, 1996; VOORA, THRIFT, 2010).

After that the sum of the emergetic flow occurring in each space was obtained. That flow consists of the quantity of emergy incorporated based on the input and output of energy flows of a system. In that way it was possible to obtain a value for the of the emergy per person by dividing each emergy flow by the population of the country. Lastly, the BC was estimated by dividing the result of the preceding stage for each ecosystem by the Global Emergy Density (GED) factor (Equation 5). Emergy Density can be defined as the emergy flow per unit of time and area and it serves to enable comparisons to be made among different ecosystems and to indicate the level of human activity in the respective areas.

$$\text{Biocapacity (gha/cap)} = (\Sigma\ \text{Rf}) / \text{GED} \qquad \text{Equation 5}$$

E Where, Rf= Renewable flow per capita in seJ/cap; GED = Global Emergy Density in seJ/gha. The GED value used in this study, 3.10 E +14, was calculated as the ratio of the planet's total renewable emergy to its area expressed in global hectares (gha). The gha unit represents the quantity of hectares of productive lands and waters with world average productivity needed to sustain the world population's consumption patterns. In addition, it provides information on the quantity of emergy needed to maintain the structure and functions of a given ecosystem or region (Odum, 1996, 2000; Pereira, Ortega, 2012).

e) Extreme Scenarios Simulation

Equations 1, 2 and 3, used earlier to determine energy flows, made it possible to identify that the parameter 'remaining vegetation stands' has an expressive impact on the final energy flow results and consequently on the BC itself. However, with the intention of demonstrating the importance of preserving the biomes and their environmental functions, this study conducted three analyses with two different approaches

The first analyzed the current state of the Brazilian biomes' BC considering their state of degradation. To that end data on the remaining stands of preserved vegetation cover in the biomes was obtained from the Ministry of the Environment, the MMA (2016) and the NGO SOS Atlantic Forest, SOS MA (2016). The second analysis consisted of a simulation of the BC considering a situation whereby the seven biomes had 100% of their vegetation cover intact, that is, without anthropic alterations. That could be considered as a scenario of complete harmony between human development and environmental conservation. The third analysis simulated a drastic scenario which considered a degree of environmental degradation whereby there was only 10% of the original areas of the Brazilian biomes left. Based on those three analyses, it was possible to assess the value of the natural capital that the Brazilian biomes represent.

f) Sensitivity Analysis

Due to the possible existence of variations in the data concerning the inputs to each of the evaluated ecosystems a sensitivity analysis was performed based on standard deviations ($\pm 1\ \sigma$) of the parameters (solar radiation, average rainfall, winds and conserved areas) to evaluate the impact that variation might have on the final results. It is worth stating that the analysis was not applied to the global spaces not inhabited by humans because of the complexity involved and the lack of available and reliable data to undertake that kind of accounting.

Results

Examining the map of the winds (Figure 1a) it can be seen that the winds are most intense in the Pampas, Caatinga and Atlantic Forest whereas the Amazon has the lowest wind index of all. In regard to solar radiation (Figure 1b), the macro-regions Northeast, Southeast and Central-west of Brazil have the highest levels and that is where the Caatinga, Atlantic Forest, Coastal zone and Cerrado biomes are located. The rainfall map (Figure 1c) shows that the highest concentration of rainfall is in the Amazon and that the Caatinga has the lowest rainfall coupled with the highest solar radiation index.

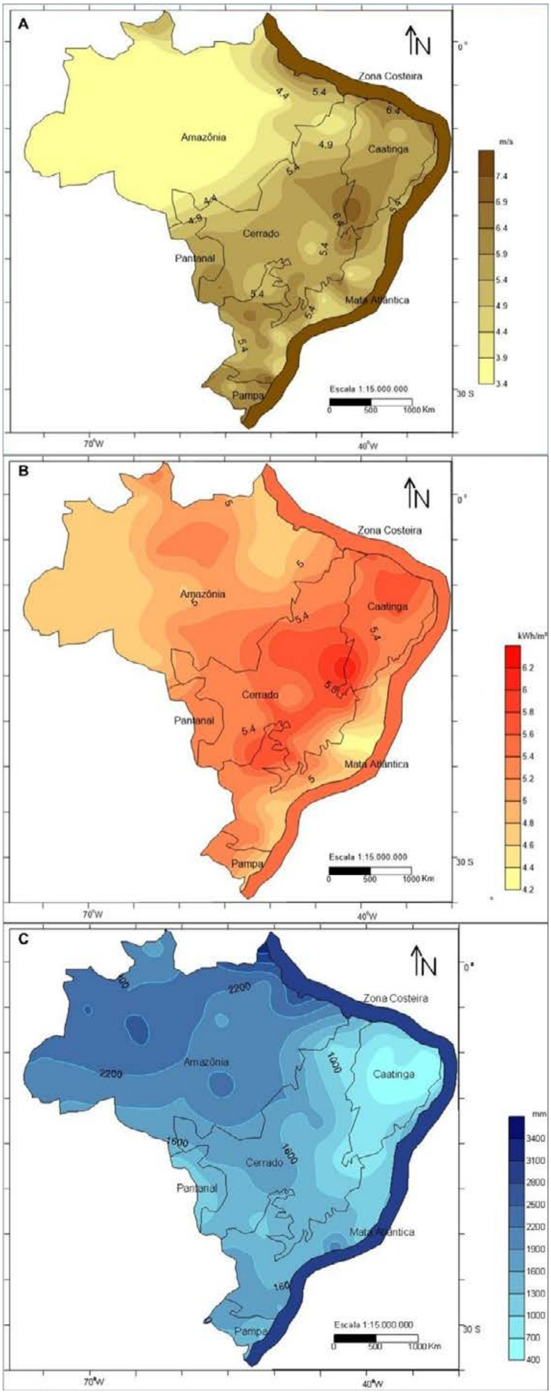
The value for solar radiation in Joules (J) obtained using equation 1 is the one that presents the highest energy potential compared with the chemical potential energy of rainfall (Equation 2) and wind (Equation 3). However, the solar contribution to the energy flow is limited by the transformity factor (Tr = 1 sej.j^{-1}), insofar as it is considered to be a primary energy source (Odum, 1996). Variables such as wind (Tr = 2.45E + 03 sej.j^{-1}) and the chemical potential of rainfall (Tr = 3.06E + 04 sej.j^{-1}) present higher transformity values and notable variations in in inter- and intra-biome intensities. In terms of Emergy (seJ), the wind is more influential in the Caatinga, in the Pampas and in the Coastal-marine zone whereas the chemical potential of rainfall is the main source of emergy for the biomes, especially the Amazon. Based on the emergetic input flows it was possible to estimate the biocapacity of the Brazilian biomes.

The Amazon contributes about half of the national BC. The Cerrado which occupies ¼ of the national territory contributes 14.8% of the Brazilian BC and the Coastal-marine zone contributes an important 17%. On the other hand, the Atlantic Forest biome which makes an expressive contribution to biodiversity and has a considerable territorial extension, contributes very little to the national BC and, indeed, the Pantanal, 7.4 times smaller contributes almost the same amount as it.

The contribution of the Brazilian biomes to the BC is 38.42 gha/cap. That is the space that each Brazilian citizen has with which to meet his or her consumption needs (water, energy, food, etc,) and with which to assimilate the residues generated by the exploitation and consumption of the natural resources (greenhouse gases, waste, agricultural chemicals). The measurement unit adopted for PE and BC accounting is the global hectare (gha) and represents the hectares of biologically productive land on the planet.

Urbanized areas make a very small contribution to the Brazilian national BC, a mere 0.3%. but the global spaces not occupied by humans contributed 3.59 gha/cap. It is important to underscore the oceans' contribution to the composition of that index and their important role in maintaining the global ecological equilibrium. In fact, the contribution of such spaces was more significant than that of the Caatinga, Atlantic Forest, Pampas and Pantanal biomes.

Figure 1 – Maps of wind occurrence (A), solar radiation (B) and average rainfall (C) in the Brazilian biomes constructed using the GIS



Source: Elaborated by the authors, 2018.

The total value of the Brazilian BC, taking emergy flows into account was 42.11 gha/cap in 2016. That figure represents the area needed to meet the consumption demands and the demands for the assimilation of each Brazilian citizen's waste. Detailed information regarding the composition of the Brazilian BC index can be found in Supplementary Document 1.

Extreme Scenarios Simulations

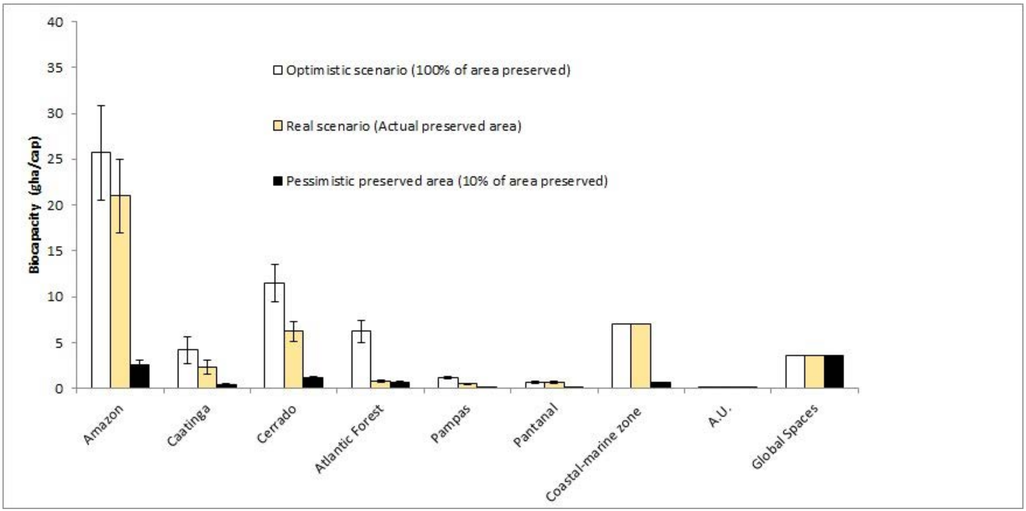
In an optimistic view, considering a scenario of complete preservation of the vegetation cover (100%), it can be seen that the biomes with the greatest territorial extensions, Amazonia, Cerrado, Atlantic Forest and Caatinga could potentially expand their BC indexes (Figure 2). If that hypothetical expanded index were actually achieved, the overall set of biomes would have a BC of 59.9 gha/cap, an increase of 42% over the BC for the year 2016. The Atlantic Forest biome presented considerable variation in the BC value; an increase of 5.43 gha/cap (about 690% more than in 2016). The second biggest percentage increase in biocapacity was that of the Pampas biome (around 115%). The variation in the Cerrado biome corresponded to an increase of 5.25 gha/cap (84%). The Caatinga also presented an increase in biocapacity of 1.86 gha/cap (82%). Variation for the Amazon biome was a mere 22%; however, that corresponded to a significant increase of 4.71 gha/cap.

The simulation of the pessimistic scenario with only 10% of the vegetation preserved shows that the BC would be reduced by 9.2 gha/ and would be four times lower than in 2016. The Pantanal and the Amazon would have BC reductions of around 90% and the Cerrado, of 5.08 gha/cap (82%), whereas the Atlantic Forest BC would only go down by 0.2 gha/cap (21%).

Sensitivity Analysis

Based on the standard deviations in the parameters of the inputs to each biome (± 1 σ) a high variability in the output data of each ecosystem was detected. That analysis was only conducted with the data for 2016. Similarly to what was observed in the extreme scenario simulations, the greatest deviations were observed (in decreasing order) in the Amazon (± 4 gha/cap), Cerrado (1.09 gha/cap), Caatinga (0.75 gha/cap) and Atlantic Forest (0.15 gha/cap) biomes. In the case of positive standard deviation, the BC value was found to be 48.31, 15% higher than the average value. In the case of a negative one the BC value was 35.92 gha/cap, 17% lower than the average value.

Figure 2 – Simulation of average biocapacity of the Brazilian biomes, comparing them to the year 2016. Vertical columns indicate the standard deviations



Source: Elaborated by the authors, 2018.

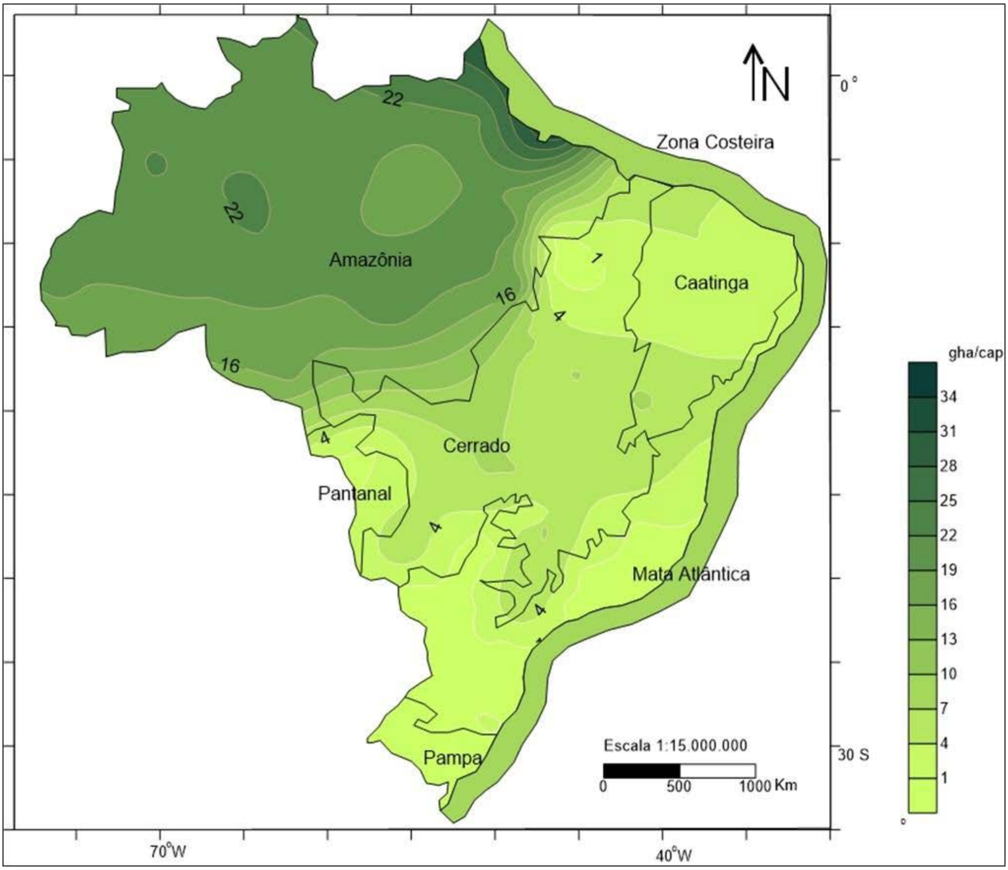
The Coastal-marine system BC did not present variations in the scenario simulations due to the absence of vegetation cover and/or the lack of data on the degradation of that biome.

Map of the Biome BCs

Every Biome has some unique characteristics that determine its general aspect and make it distinguishable from other biomes but that does not mean a uniform pattern is observable throughout its territorial extension. With the aim of showing how the variations of the input parameters at each point of the biome’s coordinates have an impact on its BC, the study used GIS to enable the elaboration of the map of the Brazilian Biomes BCs (Figure 3).

It can be seen from the Map (Figure 3) that some biomes have very abrupt BC variations within their domains. The Amazon BC for example can vary from 4 gha/cap to 34 gha/cap. On the other hand, the conformations of the Pampas, Atlantic Forest, Pantanal and Caatinga BCs are more homogeneous. The results of the sensitivity analysis corroborate the earlier statement about the variability of climate data. That climate diversity has a direct influence on the emergy flows of the natural resources within each territory.

Figure 3 – Map of the biocapacity distribution of the Brazilian Biomes.



Source: Elaborated by the authors, 2018.

Discussion

Brazil is the nation with the biggest BC on the planet but its EF has been getting bigger during the last 50 years, jeopardizing the country's ecological balance (SARKODIE, 2021). Hallis et al. (2006) made the first quantification of the Brazilian BC using the conventional EF method and estimated it as 9.9 gha/cap. Venetoulis and Talberth (2007) used an EF method based on Net Primary Productivity (NPP) and suggested that the BC was 29.16 gha/cap. In their work published in 2012, Pereira and Ortega estimated that in the year 2008 Brazil's BC was 64.71 gha/cap. According to those authors, the Brazilian biomes made a considerable contribution of 45.21 gha/cap to the composition of the total value. They proposed inserting the 'global spaces not occupied by humans' (deserts, oceans, glaciers) in the composition of the BC value calculation and the present study has adopted their proposal.

In the present work we estimate the BC of the Brazilian biomes to be 42.11 gha/cap whereas

Pereira and Ortega (2012) estimated it as 49.5 gha/cap, meaning that between 2008 and 2016 there was a reduction of around 15% in the Brazilian BC. The BC value expresses the area of the ecosystems needed to meet the demands of each Brazilian citizen; each citizen would have a useable quota of 42 global hectares of area (WACKERNAGEL et al., 2005). It must be underscored that the global hectares per annum unit (gha) does not represent a real value in itself, but it is representative of the balance between the availability of natural resources and the impacts caused by environmental pollution.

Comparing the EF and the BC is a way of interpreting how healthy the balance is, at the regional level, between anthropic activities and the ecosystems. The relationship between those two indicators reports on the 'ecological balance' of a given region (city, state, country, etc.).

One of the premises for both development and sustainability to be feasible is that the BC should be greater than the EF as that would represent a positive ecological balance (YUE et al., 2013). Thus, the monitoring of those two sustainability indicators can be used in public policies that seek to obtain an economic and social development model in equilibrium with the support capacity of native ecosystems. Monitoring those indicators would make it possible to foresee the adoption of measures such as reforestation and planning the expansion of urban nuclei; measures that seek a harmonious model for society's development (WACKERNAGEL, 2005).

Estimating BC using NPP and Emergy approaches reflects the reality of an area better than conventional EF which normally presents sub-estimated values and accordingly its representativity and functionality are being questioned (GALLI et al., 2016). Nevertheless, even emergy analysis has its limitations A debate is in course on the composition of the emergetic transformity factor of certain items due to the great complexity of measuring some systems (BIA et al., 2015). Other aspects that must be considered are the geographic location where the flow is being measured and the seasonality of the climate given that emergy is a transformation factor that expresses how much solar energy (J) is needed to generate a unit of a given resource (product, energy, process) being produced (ODUM, 1996).

It should be noted that the transformity factors are highly mutable over time and their measurement will depend on the level of application of the methodology. However, when we account for the energy flows in a process or product with an emergy approach, it incorporates some aspects that conventional EF does not consider such as the force involved in human efforts, soil loss and waste disposal in the environment, for example (BAI et al., 2015), externalities that the actual economic system does not take into account. It is essential that all the transformities used should consider the same baseline if comparisons are to be made. In their work Brown et al. (2016) propose that the energy of the waves and geothermal and solar energy (seJ.J-1) should be the baseline of the emergetic transformity factors because they are susceptible to more rigorous measurement. They estimated the baseline of the biosphere as 12.1 E+24 sej.year^{-1}.

The main contribution of the present study is the creation of a modelling that makes it possible to estimate the BC of the Brazilian biomes and understand the distribution of the (solar radiation, wind and vegetation cover) energy flows and exhibit the results in map form. Integrating the Ecological Footprint methodology with georeferenced climate data is fundamental for mapping and estimating the supply, consumption and impact of resources at different levels of scope (MELLINO et al., 2015; YANG et al., 2018). There is evidence that the EF indicator is more realistic when used in convergence with georeferenced data and emergy (ZHOU et al., 2009; SUN et al., 2015). The association of those techniques can provide a more faithful representation of the effect of anthropic pressures on the ecosystems and of the ecosystems' environmental state (MELLINO et al., 2015; YANG et al., 2018).

This article proposed a model that considered the sum of the renewable energy flows into Brazilian ecosystems namely, solar radiation, winds and the chemical potential energy of rainfall, whereas earlier estimates by Zhao et al. (2005) and Pereira and Ortega (2012) only considered the chemical potential energy of water as being the main emergetic flow into bio-productive spaces. Furthermore, for practical reasons, those earlier authors chose to use average values for that single resource whereas the present study was based on the use of three climate parameters estimated using geo-referenced information obtained from various points in the Brazilian territory. That procedure led to a considerable improvement in the BC estimate insofar as it took into account the climate variations within the respective biomes.

Results have been expressed in units *per capita* and the population figures used in BC calculations were those for the Brazilian population except for the global spaces for which world population figures were used. It is suggested that future work could use the number of inhabitants in the respective biome. That would certainly confer greater accuracy on the BC maps. This study considered the Brazilian population as it was in 2016, that is, 206 million inhabitants (IBGE, 2016). For study purposes the population was distributed evenly among the biomes.

The sensitivity analysis (Standard deviations presented in Figure 2) revealed that even slight variations in the biome input parameters lead to great changes in the output data in each ecosystem. The results show that apart from the territorial area, forest vegetation cover and population are the factors that most significantly affect the BC value. Unlike the area of the biome, population and vegetation cover are aspects that can be manipulated by the implementation of public policies orientated by a model for Sustainable Development in Brazil.

The simulations of the two forest vegetation cover situations (10% and 100%) made it possible to clearly visualize how important the presence of native vegetation is. That visualization showed the need to elaborate program and policies designed to make the Brazilian population aware of environmental issues and of the need to conserve the natural capital of the biomes to support the demands of human beings. Santiago and Couto (2020) demonstrate the clear relation between deforestation rates and Brazil's socioeconomic development in the early years of this century and underscore the model's lack of sustainability, given the ephemeral character of the natural resources that have been driving the country's development indexes. Some initiatives have been unfolded since the institution of the Brazilian Forest Law (1934, 1965) and the issuing by decree of Law Nº 12.727, dated October 17, 2012, which in its Article 1A "[...] establishes general regulations governing protection of the vegetation, areas of Permanent Preservation, and areas of Legal Reserve; forest exploitation, forest material supply, the control ands prevention of forest products origins, and the control and prevention of forest fires and makes provision for economic and financial instruments to achieve those objectives" (BRASIL, 2012).

However, what has been seen in recent years is the progressive destruction of native forests and a consequent drop in the BC of the most affected biomes. Burning, the expansion of the agricultural frontier and cattle raising are the main drivers of native vegetation loss. In the

Amazon and the Cerrado, for example, deforestation has been intensifying in recent years and the current government's actions are aggravating that situation (TRIGUEIRO et al., 2020; WEST, FEARNSIDE, 2021).

The sensitivity analysis results show how the behavior of the climate variables influences the energy flows of the natural resources within each territory. The natural variability of climate data of each biome is only to be expected but uneven distribution of the climatological seasons in the territory under study certainly contributes to increasing experimental error.

The Atlantic Forest biome has suffered intense degradation over the last few centuries and even prior to the advent of the Portuguese, from the actions of the indigenous peoples (DEAN, 1995). The BC of the biome would increase considerably if the forest vegetation cover were expanded. Today the area of native forest is a mere 12.5% of the whole (MMA, 2016; SOS MA, 2016), a value quite close to the one selected for the pessimistic scenario simulation, and that fact has a negative impact on the BC indicator. It also calls attention to the biome's environmental vulnerability and the urgent need to make decisions directed at preserving and regenerating it. It is the Brazilian biome most threatened by anthropic activities, is home to 72% of the Brazilian population and because it has one of the highest levels of endemism it is classified as a global biodiversity hotspot (ALMEIDA, 2016).

The Amazon, because of its high percentage of preserved areas, rainfall and territorial vastness presented the greatest contribution to Brazilian BC composition, around 50%. With over 1.5 million catalogued species, the Amazon is considered to be the world's largest biodiversity reserve. However, its sustainability is under threat (UBIRAJARA et al., 2016). Estimates indicate that between 2000 and 2008 deforestation was intense and it started to increase again in 2014 (CERRI et al., 2007; WEST, FEARNSIDE, 2021). The Brazilian government has implanted some public policy programs (PRODES, DETER, PMABB) in an effort to monitor and curb the problem (MMA, 2016).

Around 20 million people inhabit the vast Cerrado biome which occupies ¼ of the Brazilian land surface and contributes 14.8% of the national BC. The Cerrado is also one of the world hotspots because of the abundance of endemic species. It is acknowledged to be the richest savannah in the world with over 11 thousand native species. According to Sawyer (2009, deforestation is proceeding at a rate of 30,000 km^2 a year.

The semi-arid climate and deforestation make the Caatinga biome extremely fragile and susceptible to desertification (NUNES CARVALHO et al., 2010). The Pampas and the Pantanal are the smallest Brazilian biomes (IBGE, 2019). The Pampas is made up of highly biodiverse natural ecosystems that support environmental services of fundamental importance such as water resource conservation, genetic resource provision, availability of pollinators, and others (PILLAR et al., 2009). In turn, the Pantanal has one of the larges continuous areas of wetland in the world and it has a unique biodiversity. In spite of its small area compared to the Atlantic Forest the Pantanal makes a similar contribution to the national BC. That can be explained by the greater coverage of forest vegetation in the Pantanal.

The Coastal-marine system makes a significant 17% contribution to the Brazilian BC. the biome's continental part is occupied by Pioneer Formations (Restinga, mangrove swamps, dunes, etc.) under marine and fluvio-marine influences and it is accompanied by a strip of sea that extends 200 nautical miles out from the shore (IBGE, 2019). The land portion is complex, dynamic, highly mutable and subject to the action of various geological processes between the marine and terrestrial domains, The Coastal-Marine system is suffering de-characterization from anthropic actions mainly related to land use and occupation (AMARAL, JABLONSKI, 2005; LINS-DE-BARROS, 2017).

The positive balance of the Brazilian BC (42 gha/cap) and the fact that Brazil has the biggest BC of all nations (SARKODIE, 2021) does not mean that the situation cannot be improved. There is much to be done in terms of improving the quality of the Brazilian ecosystem services. Examples are the expansion of Protected Areas, reduction of deforestation through enhanced inspection and surveillance of the illegal exploitation and trading of renewable resources, and the use of sustainable agricultural techniques and sustainable energy sources (Law Nº 9.478, 1997). That means it is of fundamental importance to have policies designed to raise the awareness of society in regard to environmental issues and the need to maintain and preserve the Brazilian ecosystems.

The forecasts set out in the report of the IPBES (2018) reinforce the need for monitoring and identifying the ways in which preserved areas can be occupied because the long-term extrapolations of the ecosystems' limits may cause economic and social collapses in the future, as has been shown for many regions at the global level. That report highlights how, up to the moment, only 25% of terrestrial ecosystems have not suffered significant impacts and it foresees a shocking reduction of that figure to 10% by the year 2050. The places most vulnerable to expressive losses are Sub-Saharan Africa, Asia and South and Central America (IPBES, 2018). The efficacy of the method this paper has applied can be further improved by gathering field data from a denser sampling network which would lead to a better calibration.

The lack of reliable Coastal Zone data concerning the size of the preserved areas, climate information, and measurements of impacts on the environment have made any estimate of the BC of that ecosystem imprecise. The analysis of that biome presented here does not include areas of pasture, crops or forest vegetation but it should be possible to insert new variables to achieve further calibration of the model and improve the results. Regional and temporal variations, and variations in the system producing the goods and services consumed in a given location influence the transformity factors. This last aspect requires more detailed investigation and primary data generation at the local level for the model to acquire greater precision. It is suggested that the climate maps (Figures 1 and 3) could be further refined by using the available data in a raster data storage format which provides higher spatial definition (FICK e HIJMANS, 2017).

Conclusions

In the year 2016, the biocapacity of the Brazilian biomes was 42.11 gha/cap. That value expresses the ecosystem area that each Brazilian needs to absorb the generated pollution and meet his or her demand for natural resources. The Amazon and Coastal-marine biomes contributed significantly to that value due to their high amounts of natural capital, their huge areas and the conservation of the Amazon forest.

To increase the Brazilian BC, it would be feasible to adjust 'preserved areas' and 'population' parameters by means of public policies orientated by a Sustainable Development model. That means it is of fundamental importance to have policies to make society aware of environmental issues and the need to maintain and preserve the Brazilian ecosystems. Among the mechanisms that could have a positive impact on the Brazilian BC, especially the Atlantic Forest and Cerrado biome are: compliance with the environmental legislation in force in Brazil, especially the Forest Law and the Native Vegetation Protection Law; expanding the number of protected areas; and promoting environmental education campaigns.

The results of the present study can be used to support decision-making on the use of natural resources and its relations with the environment. Using geo-referenced data proved to be useful for observing the BC mosaic of each of the studied biomes in the maps. Potentially, that methodology could be replicated at local or regional levels. For future research, it is suggested that the interpolation techniques and the real-time gathering of climate and demographic data could be calibrated enabling even more detailed and more precise results to be obtained.

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Wallan Azevedo dos Santos
🖂 wallan.azevedo@hotmail.com
ORCiD: https://orcid.org/0000-0002-5925-4908

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Milton Erthal Junior
🖂 miltonerthal@hotmail.com
ORCiD: https://orcid.org/0000-0002-9959-3568

Renato Gomes Sobral Barcellos
🖂 rgsbarcellos@gmail.com
ORCiD: https://orcid.org/0000-0002-8989-9985

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Biocapacidade dos biomas brasileiros a partir de conceitos da pegada ecológica emergética

Wallan Azevedo dos Santos
Milton Erthal Junior
Renato Gomes Sobral Barcellos

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Artigo Original

Resumo: O objetivo deste trabalho é avaliar a biocapacidade (BC) dos biomas brasileiros utilizando os conceitos da Pegada Ecológica Emergética. Dados climáticos e da cobertura florestal foram interpolados pelo método de Kriging. No ano de 2016, a BC brasileira foi de 42,11 gha/cap, uma das maiores do mundo. A área de cobertura florestal foi investigada e simulada em dois cenários: otimista (com 100% de cobertura florestal) e pessimista (apenas 10%). A Amazônia, que contribui com metade da BC brasileira, reduziria sua contribuição em 88% em um cenário pessimista. A Mata Atlântica contribuiu com apenas 1,9% da BC nacional, contudo, em um cenário otimista, aumentaria em 690% sua contribuição. A redução do desmatamento, das queimadas e a expansão das áreas protegidas por lei são medidas que impactam positivamente a BC dos biomas estudados. Esta metodologia pode ser empregada como um indicador da qualidade ambiental pois é aderente aos princípios do Desenvolvimento Sustentável.

***Palavras-chave*:** Desenvolvimento Sustentável; Emergia; Indicadores de Sustentabilidade; Gestão Ambiental.

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BIOCAPACIDAD DE BIOMAS BRASILEÑOS BASADOS EN CONCEPTOS DE LA HUELLA ECOLÓGICA EMERGÉTICA

Wallan Azevedo dos Santos
Milton Erthal Junior
Renato Gomes Sobral Barcellos

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Artículo original

Resumen: El objetivo de este trabajo es evaluar la biocapacidad (BC) de biomas brasileños utilizando los conceptos del método de Huella Ecológica Emergente. Los datos sobre el clima y la cobertura forestal se interpolaron utilizando el método Kriging. En 2016, el BC brasileño era de 42,11 gha / cap, uno de los más grandes del mundo. El área de cobertura forestal de los biomas fue investigada y simulada en dos escenarios: optimista (con una cobertura forestal del 100%) y pesimista (solo el 10%). La Amazonia, que aporta la mitad del BC brasileño, reduciría su contribución en un 88% en un escenario pesimista. La Mata Atlántica aportó sólo el 1,9% de la CB nacional, sin embargo, en un escenario optimista, aumentaría su contribución en un 690%. La reducción de la deforestación, los incendios y la expansión de áreas protegidas por ley son medidas que impactan positivamente la CB de los biomas estudiados. Esta metodología se puede utilizar como indicador de la calidad ambiental ya que se adhiere a los principios del Desarrollo Sostenible.

Palabras-clave: Desarrollo Sostenible; Emergía; Indicadores de Sostenibilidad; Gestión ambiental.

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