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INTEGRATED ENVIRONMENTAL FOOTPRINT INDEX (IEFI): MODEL DEVELOPMENT AND VALIDATION

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ABSTRACT: Freshwater is a valuable resource worldwide given the growing demand of the global population. This study aimed to develop and validate an integrated assessment model by means of environmental footprint indices (water, ecological, and carbon), which measure the environmental sustainability of heterogeneous communities, people, and countries. An environmental footprint was firstly defined as a set of indicators to track human pressure on planet Earth under different angles, being a multidimensional index of environmental sustainability. A Delphi survey was used to bring together opinions from a diverse set of experts. The participants of this study consisted of 120 experts from several fields of knowledge belonging to the best-known research and education institutions in Brazil. Through this technique, an integrated environmental footprint index (IEFI) could be developed, being then validated with information from eight different communities located in the Paraíba State (Brazil). Afterwards, this index was applied to several representative countries from all continents. Our results indicated the sensitiveness of IEFI model to variations in natural ecosystems, in addition to its ability to identify the environmental balance of a person, community, or nation level.

KEYWORDS: water footprint, CO_2 emissions, natural resources.

INTRODUCTION

A balance between socio-economic and environmental sustainability requires the understanding of economic flows and biological capacity needed to absorb environmental impacts of human activities (Silva et al., 2013a). In the early 1990s, the concept of ecological footprint (EF) was introduced as a measure of human appropriation of biologically productive areas (REES, 1992, 1996; Wackernagel & Rees, 1996). Later, Hertwich & Peters (2009) worked on the concept of carbon footprint (CF) to measure the total amount of greenhouse gases (GHG) over product life cycle. A similar concept, called water footprint (WF), was introduced to measure human appropriation of freshwater throughout the globe (Hoekstra & Huang, 2002). Although both concepts have different roots and methods of measurement, in some aspects both of them translate the use of natural resources by humanity (Hoekstra et al., 2009). EF expresses space use (in hectares) whereas WF measures the total use of freshwater resources (in cubic meters per year).

Elaborating environmental sustainability indicators contemplating WF, EF, and CF can be a constructive initiative to study the environment, in addition to being incipient worldwide. In this sense, several attempts have been made to develop an integrated approach of these footprints for environmental and consumption influences (Giljum et al., 2011). In this regard, Galli et al. (2012) proposed, for the first time, an integrated concept of a family of footprints as a set of indicators to monitor human pressure on the planet. No sustainability indicator alone is able to monitor comprehensively human impacts on the environment (Galli et al., 2013). These authors also claimed the need for using and interpreting sustainability indicators jointly for environmental impacts from production and consumption sectors.

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The central hypothesis of this study is testing the efficiency of an integrated model of environmental footprints, called as hydrological, ecological, and carbon footprints in assessing the degree of environmental sustainability of individuals, communities, and nations. In this sense, this study aimed to elaborate and validate a model based on water, ecological, and carbon footprints to measure the level of environmental sustainability of heterogeneous communities, people, and countries.

MATERIAL AND METHODS

This research was carried out in eight heterogeneous communities of the Paraíba State, in Brazil: (i) Indigenous (town of Baía da Traição); (ii) Quilombola Ypiranga (town of Conde); (iii) Naturist Tambaba (town of Conde); (iv) Fishermen of the Praia da Penha (town of João Pessoa); (v) Rural Settlement of Santa Helena (town of Sapé); (vi) Large-sized City (town of Campina Grande); (vii) Medium-sized City (town of Guarabira); and (viii) Small-sized City (town of Araruna). In the field research, any individual over 18 years old, with sufficient insight to answer questions regarding water, ecological, and carbon footprint questionnaire was considered as the target population.

A simple random probabilistic sampling was used. In this type of sampling, participants were chosen at random from a lottery of participants. In this case, each population member has the same probability of being chosen. Thus, 20 social actors were interviewed for the first five communities (Indigenous, Quilombola, Naturist, Fishermen, Rural Settlement) and other 100 for the last three communities (Campina Grande, Guarabira, and Araruna) taking into account the total number of inhabitants. Data collection for footprint calculation was performed by means of interviews based on a structured script reasoned by a questionnaire. The interviews took place through direct and personal contact with the subjects of the research, where the researcher was responsible for planning, conducting, and collecting the data from the interview.

In this study, the Delphi research was used as a methodology for congruence. In the first round, invitations were sent to 120 experts from the most diverse fields of knowledge from the most renowned research and education institutions in Brazil in order to participate in our research. For this, 90 panelists accepted the invitation and confirmed participation. Then, a second round was carried out containing the structured questionnaire with 36 questions involving the Dimension 1 or water footprint with three questions, Dimension 2 or ecological footprint with 17 questions, and Dimension 3 or carbon footprint with 16 questions for the experts to choose the indicators they considered more important for each dimension. After receiving second round results, they were resent to the same panelists to a third round evaluation taking into account the opinion of the other panelists, always preserving the anonymity, which is essential in this process. After the re-evaluation of panelists' replies, the congruence of responses was reached in the fourth round. In Dimension 1, all three suggested indicators were validated; in Dimension 2, among the 17 suggested indicators, four of them were validated; and in Dimension 3, five indicators were validated among the 16 suggested. The validated indicators of each dimension are italicized and underlined in Table 1. Another Delphi research was carried out to determine which of the water, ecological, and carbon footprints the panelists considered as more important in characterizing the environment, being assigned weights between 0 and 1. In addition, in the fifth round, the congruence of responses was reached, serving to determine the weights for the relative coefficients in each one of the dimensions of the proposed index.

TABLE 1. Dimensions and indicators involved in water, ecological, and carbon footprint calculations.

Dimension	Indicator
1. Water footprint	- _Gender_* - _Consumption of meat_* - _Gross income per year_*
2. Ecological footprint	- _Consumption of meat_* - Consumption of fish - Consumption of milk, dairy products, and eggs - _Amount of consumed food being produced in Brazil_* - Monthly value for the purchase of clothes and footwear - Annual value for the purchase of home appliances, work tools, including gardening - Annual value for the purchase of computers or electronic equipment - Monthly value for the purchase of newspapers, magazines, and books - Amount of paper and glass consumed and separated for recycling - _Number of people residing at home_* - Amount of area at home - Use of energy-saving bulbs at home - Percentage of electricity use coming from renewable resources - _Monthly average consumption of electricity at home_* - Average distance traveled as a driver or passenger per week - Average distance traveled by public transportation per week - Total flight hours per year
3. Carbon footprint	- Number of people residing at home - _Average consumption of electricity_* - Average consumption of cooking gas - Total flight hours per year - _Amount of own vehicle_* - Use of public transportation - Consumption of meat - _Consumption of organic products_* - Consumption of season food - Consumption of imported food - _Consumption of clothes_* - Consumption of packaging - Consumption of furniture and electrical appliances - Products consumed and separated for recycling* - Destination of free time - Use of financial services or other types

*Validated indicators are italicized and underlined

Based on the data collected in the eight heterogeneous communities of the Paraíba State, water (WF), ecological (EF), and carbon footprints (CF) were assessed for each of them. Thus, this study proposes to apply the model called integrated environmental footprint index (IEFI), which integrates all the impacts a person, a community, a city, a state, and even a country can have on the environment. This model uses the family of environmental footprints, integrating the consumption of freshwater (WF), territorial area extension a person or a whole society uses to sustain itself (EF), and greenhouse gas emissions (CF) in a single index by [eq. (1)]:

$$\mathrm{IEFI}_i = \left(\frac{\mathrm{WF}_i}{\mathrm{WF}_w} \times 0.36 + \frac{\mathrm{EF}_i}{\mathrm{EF}_w} \times 0.35 + \frac{\mathrm{CF}_i}{\mathrm{CF}_w} \times 0.29 \right) \tag{1}$$

where,

IEFI_i is the integrated environmental sustainability index of the community *i*,

WF_i, EF_i, and CF_i are, respectively, the averages of water, ecological, and carbon footprints of the community *i*, and

WF_w, EF_w, and CF_w are, respectively, the world averages of water, ecological and carbon footprints.

The coefficients 0.36, 0.35, and 0.29 were determined using the Delphi methodology, as previously described. Thus, when IEFI < 1, the community *i* is environmentally sustainable and when IEFI ≥ 1, the community *i* is environmentally unsustainable (Table 2).

TABLE 2. Classification of the integrated environmental footprint index (IEFI).

Classification	Value of IEFI
Unsustainable	IEFI ≥ 1.00
Critical	0.80 ≤ IEFI <1.00
Alert	0.60 ≤ IEFI < 0.80
Moderately acceptable	0.40 ≤ IEFI < 0.60
Acceptable	0.20 ≤ IEFI < 0.40
Ideal	0.00 ≤ IEFI < 0.20

IEFI levels classified as sustainable (IEFI < 1) and unsustainable (IEFI ≥ 1) were divided into five levels of sustainability. IEFI is defined as an index formed by a set of indicators capable of expressing human pressure on the environment, with the monitoring of the biosphere, atmosphere, and hydrosphere using carbon, ecological, and water footprints. The primary data were obtained based on questionnaires applied to the inhabitants of eight heterogeneous communities of Paraíba State. Questions were elaborated according to the source of information needed for each dimension, being (i) water footprint based on the Quick Calculator, (ii) ecological footprint based on the Global Footprint Networks, and (iii) carbon footprint based on the Carbon Footprint Company.

RESULTS AND DISCUSSION

Naturist and Fishermen were the communities showing the highest WF values whereas the Indigenous and Quilombola communities presented the lowest IEFI (Table 3). The result found for Naturist is surprising since a more balanced environmental consciousness for this community would be expected and not an IEFI condition classified as critical. The average WF index for the studied communities is below the world average of 1,385 m^3 per person per year (Hoekstra & Mekonnen, 2012). However, the communities Naturist, Fishermen, and Large-sized City presented average WF values above the world average due to the higher per capita income and consumption habits of their inhabitants. On the other hand, the communities Quilombola and Indigenous, which have a lower per capita income and reduced consumption habits, presented low WF values, in addition to presenting great social and economic problems.

The average EF values of the analyzed communities were lower than the world average of 2.7 hectares. Thus, all the analyzed communities presented average EF values below the world average. Similarly, the average CF value of the analyzed communities was much lower than the world average of 4.0 tons of CO_2 per year. As for EF, all communities presented average CF values lower than the world average. Therefore, these communities still have habits of consumption, lifestyle, and environmental practices considered as sustainable from the point of view of the water, ecological, and carbon footprints.

TABLE 3. Average of integrated environmental footprint indices (IEFI) of heterogeneous communities as a function of water (WF), ecological (EF), and carbon footprints (CF).

Community	**WF** (m^3/person/year)	**EF** (global hectares)	**CF** (tons of CO_2/year)	**IEFI**
Fishermen	1,593	1.73	1.68	1.68
Quilombola	672	1.66	1.11	1.11
Rural settlement	881	1.77	1.13	1.13
Naturist	2,144	1.66	1.82	1.82
Indigenous	856	1.63	0.82	0.82
Large-sized City	1,548	1.85	1.60	1.60
Medium-sized City	1,303	1.79	1.47	1.47
Small-sized City	1,065	1.72	1.40	1.40
Mean	**1,258**	**1.73**	**1.38**	**1.38**

This result is particularly important because although the world population has quadrupled global water consumption in the last century and the emissions of residues have grown to the point where humanity consumes faster than the Earth can regenerate (Hoekstra & Chapagain, 2008), some localities still have certain ecological balance. The high values of ecological footprints and hence IEFI are affected by the economic and social development of communities. The communities Quilombola, Indigenous, and Small-sized City presented IEFI values within the range moderately acceptable whereas the communities Medium-sized City, Fishermen, and Large-sized City were classified as alert and the community Naturist as critical. This result is particularly important since this latter community was expected to have a very well balanced IEFI with the environment. However, people going into this area should transfer their consumption habits from medium- and large-sized cities and are not effectively practicing naturism as a philosophy of life, but only nudism.

The average WF of the African countries analyzed in this study is considered high (1,500 m^3 per person per year), considering a world average of 1,385 m^3 per person per year (Hoekstra et al., 2009). The highest WF was found in Niger, on the African continent (Table 4). This high WF value is partially justified because Niger is an importing country of virtual water contained in the food consumed by the population. However, the average values of EF and CF are below the world average, being the average IEFI of this continent classified as moderately acceptable (Table 2). Products coming from agriculture have a high virtual water content since the agricultural activity present a high blue water consumption (Silva et al., 2013b).

Tunisia is the country with the second highest index of WF of the African continent whereas Gambia and Zambia presented the lowest average values. The results still indicate an average WF below the world average for 61.11% of the African countries analyzed in this study. The big problem is the other countries (38.89%) making WF average of Africa increase very much, surpassing the world average. The average EF of Africa is 1.85 global hectares, which is below the world average of 2.7 hectares. On the other hand, its average WF is higher than the world average. The CF of Africa, 0.47 tons of CO_2 per year, is well balanced since the worldwide average is 4.0 tons of CO_2 per year (Hoekstra & Mekonnen, 2012). In addition, all analyzed countries have an average CF below the world average.

Considering the averages of IEFI presented by the studied African countries and taking into account the scale of sustainability levels proposed in this study, the average values for Africa are within the moderately acceptable range. Only Mauritius, Niger, and Libya presented IEFI values classified as unsustainable.

TABLE 4. Water footprint (WF), ecological footprint (EF), carbon footprint (PC), and integrated environmental footprint index (IEFI) of countries by continent.

Country	WF	EF	CF	IEFI
Africa				
South Africa	1,255	2.32	1.31	0.72
Angola	958	1.00	0.16	0.39
Cameroon	1,245	1.04	0.12	0.47
Egypt	1,341	1.66	0.62	0.61
Ethiopia	1,167	1.10	0.06	0.45
Gambia	887	3.45	0.29	0.70
Ghana	1,027	1.75	0.25	0.51
Libya	2,038	3.05	1.92	1.06
Madagascar	1,576	1.79	0.07	0.65
Malawi	936	0.73	0.05	0.34
Mauritius	2,161	4.26	1.49	1.22
Morocco	1,725	1.22	0.33	0.63
Namibia	1,682	2.15	0.58	0.76
Niger	3,519	2.35	0.04	1.22
Nigeria	1,242	1.44	0.17	0.52
Kenya	1,101	1.11	0.15	0.44
Tunisia	2,217	1.90	0.68	0.97
Zambia	921	0.91	0.13	0.37
Mean	1,500	1.85	0.47	0.67
North America				
Canada	2,333	7.01	4.03	1.89
United States	2,842	8.00	5.57	2.18
Mexico	1,978	3.00	1.37	1.00
Mean	2,384	6.00	3.57	1.69
Central America				
Costa Rica	1,490	2.69	0.10	0.74
Cuba	1,687	1.85	0.76	0.73
El Salvador	1,032	2.03	0.11	0.54
Guatemala	983	1.77	0.49	0.52
Haiti	1,030	0.68	0.10	0.36
Honduras	1,177	1.91	0.23	0.57
Jamaica	1,696	1.93	0.87	0.75
Nicaragua	912	1.56	0.51	0.47
Dominican Republic	1,401	1.47	0.01	0.56
Panama	1,364	2.87	0.62	0.77
Mean	1,277	1.88	0.38	0.68
South America				
Argentina	1,607	2.60	0.77	0.81
Bolivia	3,468	2.57	0.37	1.26
Brazil	2,027	2.91	0.43	0.94
Chile	1,115	3.24	1.02	0.78
Colombia	1,375	1.87	0.45	0.63
Ecuador	2,007	1.89	0.66	0.81
Paraguay	1,954	3.19	0.38	0.95
Peru	1,088	1.54	0.26	0.50
Uruguay	2,133	5.13	0.5	1.26
Venezuela	1,710	2.89	1.42	0.92
Mean	1,848	2.78	0.63	0.89
Asia				
Cambodia	1,078	1.03	0,14	0,42
China	1,071	2.21	1,21	0,65
United Arab Emirates	3,136	10.68	8,10	2,79
India	1,089	0.91	0,33	0,42
Indonesia	1,124	1.21	0,33	0,46
Iran	1,866	2.68	1,71	0,96
Iraq	1,301	1.35	0,89	0,58
Israel	2,303	4.82	3,08	1,45
Japan	1,379	4.73	3,13	1,20
North Korea	888	1.32	0,72	0,45
South Korea	1,629	4.87	3,17	1,28
Kuwait	2,072	6.32	4,53	1,69
Malaysia	2,103	4.86	3,12	1,40
Mongolia	3,775	5.53	1,24	1,79
Nepal	1,201	3.56	2,85	0,98
Pakistan	1,331	0.77	0,26	0,46
Turkey	1,642	2.70	1,24	0,87
Mean	1,713	3.59	2.20	1.03
Europe				
Germany	1,426	5.08	2.70	1.21
Austria	1,598	5.30	3.13	1.33
Belgium	1,888	8.00	3.87	1.81
Denmark	1,635	8,26	3,47	1,75
Spain	2,461	5.42	2.73	1.54
Finland	1,414	6.16	4.31	1.48
France	1,786	5.01	2.51	1.30
Great Britain	1,258	4.89	2.87	1.17
Greece	2,338	5.39	2.92	1.52
Netherlands	1,466	6.19	2.99	1.40
Hungary	2,384	2.99	1.66	1.13
Italy	2,303	4.99	2.66	1.44
Norway	1,423	5.56	1.42	1.19
Portugal	2,505	4.47	2.07	1.39
Poland	1,405	4.35	2.26	1.09
Russia	1,852	4,41	2,72	1,25
Sweden	1,428	5.88	2.73	1.33
Switzerland	1,528	5.02	3.20	1.28
Mean	1,783	5.41	2.79	1.37
Oceania				
Australia	2,315	6.20	3.11	1.63
New Zealand	1,589	8.84	2.29	2.00
Mean	1,852	7.50	2.70	1.80

This fact may be associated with the overexploitation of tourism activity in these countries, exceeding their carrying capacity. Because Niger and Libya are located in large deserts, these countries have the need to import the virtual water contained in products consumed by the population, leading to high WF values and thus increasing their IEFI values.

North American countries with the highest WF values were the United States and Canada whereas Mexico presented the lowest value. Therefore, the average WF of the North American countries is almost twice the world average of 1,385 m^3 per person per year. These countries also have the highest averages of WF, EF, and CF, leading to the highest IEFI value of the North American countries (1.86), consequently being classified as unsustainable. Canada has the second highest average of WF, EF, and CF, consequently, the second highest IEFI, being thus classified as unsustainable. On the other hand, the Mexican EF and CF values are practically a third of the United States, leading to an IEFI value below 50%, which makes Mexico at the limit of the sustainable/unsustainable range. Data from Global Footprint Network (2011) point to an increase of 2.5 times the global ecological footprint of humanity from 1961 to 2008, i.e. from 7.2 to 18.2 billion hectares. During this period, human activities surpassed nature regeneration capacity by 50%. This increase was more prominent considering the carbon footprint, which increased 3.8 times due to the increasing use of fossil fuels and electricity (Galli et al., 2014).

Central American countries with the highest WF values were Jamaica and Cuba whereas Nicaragua and Guatemala presented the lowest WF values due to the lifestyle and consumption habits of their inhabitants. Mekonnen & Hoekstra (2014) draw attention to the wide disparities in water availability and scarcity within and among countries because people and water resources are distributed unevenly across the globe. In this sense, virtual water import by agricultural product import is increasingly recognized as a mechanism to improve national water security (Konar et al., 2012). All Central American countries have average values of EF and CF below the world average. In addition, considering the IEFI values, these countries are very sustainable, with more than 50% of the continent's countries within the acceptable range ($0.20 \leq \text{IEFI} \leq 0.40$), being one of them the Haiti, with an IEFI value close to the sustainability condition classified as ideal.

Bolivia and Uruguay were the South American countries showing the highest WF values whereas Peru and Chile presented the lowest values. The average WF of this continent is above the world average. However, the average values of EF and CF are below the world average, leading to average IEFI values classified as sustainable. The average WF of the South American inhabitants is 33.4% higher than the world average and presented a large range of variation, from 1088 m^3/year per capita in Peru to 3468 m^3/year per capita in Bolivia. This is contradictory because Latin America has significant levels of malnutrition although the plenty of water for food production. Considering the global EF, South America experienced the largest net forest loss between 2000 and 2010. During this period, the net loss of forest area was 2,642,000 ha/year in Brazil, 290,000 ha/year in Bolivia, and 288,000 ha/year in Venezuela (Mekonnen et al., 2015). Extensive grazing is one of the main causes of the rapid deforestation in tropical forests of South America and it will continue the expansion mainly at the expense of forest cover.

Asian countries with the highest WF values were Mongolia, the United Arab Emirates, and Israel, which presented IEFI values classified as unsustainable. The United Arab Emirates has little arable land and its economy is mainly based on oil and natural gas exploration and tourism. These factors contribute to the high consumption of imported virtual water, causing WF increase. This country has high values of EF and CF, being well above the world averages. On the other hand, Mongolia has very little arable land, most of which covered by steppes, mountains in the north and west, and the Golgi desert in the south. In addition, most of the products consumed are imported. These countries have IEFI values close to 3.0, indicating a high unsustainability degree. However, Asia has some countries with IEFI values classified as moderately acceptable. On the other hand, on average, this continent is unsustainable, with IEFI values above the range $\text{IEFI} > 1.0$. A study highlighted China, India, and the United States as the owners of the highest total WF, with values of 1207, 1182, and 1053 G m^3/year, respectively, and with about 38% of the global WF production (Hoekstra & Mekonnem, 2012).

The European continent is very unsustainable when considering its average IEFI value of 1.37. However, all the continent's countries, except Finland, have an average CF below the world average since this country has a transportation system based on automotive vehicles, leading to a strong CO_2 emission when compared to other European countries owning a public transportation system and the use of bicycles. On the other hand, the averages of WF and EF of the other countries are above the world average. In this context, Galli et al. (2014) pinpointed the use of ecological assets by European economy, being currently of almost three times the amount available on the continent.

In fact, the European countries with the highest average WF are Portugal and Spain whereas Great Britain and Poland showed the lowest values due to their consumption habits. Australia has WF and CF values higher than New Zealand; however, the IEFI of New Zealand is higher than the one found in Australia because of its high EF value, which is three times higher than the world average. Both countries have CF below the world average, but the high average values of EF and WF led these countries to be classified as unsustainable according to the IEFI model. Central America is the continent with the lowest values of WF, EF, and CF, followed by Africa, making them the most sustainable on the planet. In contrast, North America is the continent with the highest unsustainability level, especially due to the high consumption pattern of Americans. Considering the average IEFI value of 1.16, the planet is unsustainable with the current consumption patterns, forest destruction, and pollution.

The results of this study are within the global context in which environmental changes such as deforestation and carbon dioxide accumulation in the atmosphere indicate a superior human demand to a regenerative power and absorption capacity of the biosphere (Boruckea et al., 2013). According to Rockström et al. (2009), several studies suggest the overcoming of sustainability limits of the Earth have been overcome since the demands on natural systems increase rapidly due to the need of humanity in achieving better living conditions. On the other hand, studies conducted in other regions of the world indicate semi-arid regions of Central America, West Asia, North America, and Africa as being already close to or below the water scarcity threshold of 1,000 m^3 per capita per year (Haberl, 2006).

For elaborating the IEFI model, the information needed to obtain the three environmental footprints of the eight communities located in the Paraíba State was used. On the other hand, in the validation process, this model was applied to several countries of all continents with completely different environmental characteristics regarding consumption patterns, family income level, and social and cultural levels. Thus, Figure 1 shows the relationship between IEFI and water, ecological, and carbon footprints of these countries.

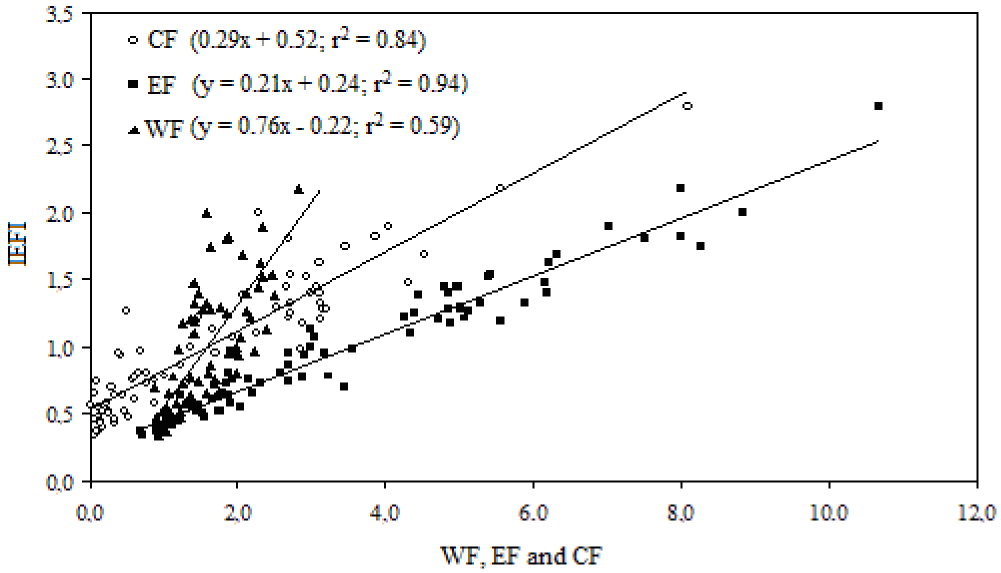

FIGURE 1. Relationship between IEFI and water, ecological, and carbon footprints for countries of all continents.

The comparison between the relationships of IEFI with the three analyzed footprints showed high coefficients of determination, the highest for ecological footprint and the lowest for water footprint. All these coefficients of determination were statistically significant by the Student's t-test at 1% probability level. Therefore, within the validation process, the model responded satisfactorily to the contrasts between countries with completely different environmental, social, and cultural characteristics. In this sense, Linstone & Turoff (2002) assure the need to keep the heterogeneity of participants to be consulted as a way for validating the study.

CONCLUSIONS

The IEFI model can be used in any geographical area of the Earth to assess the impact of human pressure on the environment. This model is sensitive to the variations of natural ecosystems, being able to identify the degree of ecological balance of a person, community, or nation with the environment. The attendees of the analyzed naturism community brought their consumption habits from medium- and large-sized cities, thus without effectively practicing naturism as a philosophy of life, given their high IEFI value. The Indigenous community, on the other hand, presented the lowest IEFI value among all the analyzed communities, being classified as moderately acceptable. For the continents, IEFI varied between the ranges alert in Africa and unsustainable in Oceania whereas the Earth was classified as unsustainable.

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