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Sustainability calculation approach of guadua (*Guadua angustifolia* Kunth.) forests throughout the use of emergetic analysis

Aproximación al cálculo de la sostenibilidad de bosques de guadua (*Guadua angustifolia* Kunth.) mediante el uso de análisis emergético

Ángela *María Arango Arango*[1]*, *Juan Carlos Camargo García*[1] *and Juan Mauricio Castaño Rojas*[2]

[1]Grupo de Investigación en Gestión de Agroecosistemas Tropicales Andinos "GATA". Facultad de Ciencias Ambientales. Universidad Tecnológica de Pereira, Colombia. [2]Grupo de investigación en Ecología, Ingeniería y Sociedad – EIS. Facultad de Ciencias Ambientales. Universidad Tecnológica de Pereira, Colombia. Author for correspondence: amarango@utp.edu.co

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Abstract

The sustainability of guadua forests under management was assessed throughout the emergy analysis approach. The system analyzed correspond to guadua forest whose major product are culms for commercial purposes. In order to calculate the sustainability, available information on purchased inputs, renewable and nonrenewable natural resources as well as external factors, which can affect the system such as labor or inputs (ie. fuel consumption), was used for calculate indexes which describe relationship among the employed natural resources. The results showed the guadua forest system under management does not depend on external inputs and its sustainability is above 90%. In fact, the recovery ability after harvesting shown by these guadua forests is associated with a proper management, which contributes to the ecosystem conservation of functions. Considering the current management conditions, the guadua forest system is sustainable although highly dependent on natural resources. Under these conditions, the system become vulnerable since the management should be focused on guaranteeing the current conditions and therefore, their conservation.

Keywords: Emergetic, farm, guadua forest system, management, renewable natural resources.

Resumen

La sostenibilidad de los bosques manejados de guadua se evaluó utilizando el enfoque emergético. El producto principal de este sistema son culmos que se cosechan para uso comercial. Para el cálculo de la sostenibilidad se utilizó la información disponible sobre insumos comprados, los recursos naturales renovables y no renovables utilizados en el proceso, así como de factores externos como mano de obra e insumos que pueden afectar al sistema. De esta manera, se calcularon índices que describen relaciones entre los recursos empleados. Los resultados mostraron que el bosque de guadua como sistema no presenta dependencia alta de uso de insumos externos y que su sostenibilidad está por encima del 90%, demostrando su capacidad de recuperación después de ser cosechado. De la misma manera, el buen manejo de estos bosques contribuye a la conservación de las funciones que cumplen como ecosistemas. El sistema, de acuerdo a las condiciones de manejo actual, es sostenible y depende altamente de los recursos naturales. Esta condición por lo tanto, puede hacerlo vulnerable, razón por la cual su manejo debe estar enfocado en garantizar las condiciones que permitan la conservación de los mismos.

Palabras Clave: Emergético, finca, manejo, sistema bosque de guadua, recursos naturales renovables.

Introduction

The guadua (*Guadua angustifolia* Kunth.) forests (dominated by the natural bamboo species), represent a local natural resource, which has gained economic and environmental relevance in Colombia, particularly in the Coffee Region (Camargo, Rodríguez & Arango, 2010). These guadua forests can be used to obtain culms traditionally used to build houses or other domestic applications (IBID). In the Colombian coffee-growing area, 28000 hectares, were estimated (Camargo, Montoya & Quintero, 2014). Many of these guadua forests have been phased out, to give way to agriculture, generating fragmentation.

Some of these guadua forests, had achieved silvicultural management and are harvested to obtain culms for domestic and/or commercial use. In fact, for this purpose, Colombian legislation standard requires an approved management plan and regulated by the competent environmental authority to ensure that management is properly carried out and the sustainability of the natural resource is not compromised.

Despite having advances in the guadua forest management and their importance as an ecosystem, few literature citations on the influence in sustainability analysis and the level of affectation associated with their use is generated. Previous studies on the life cycle of products and carbon footprint derived from guadua (*G.angustifolia*) (Arango & Camargo, 2012), show possibilities for the commercial use of these guadua forests and elements that contribute to their sustainability. However, since guadua is a renewable natural resource, it depends on factors such as solar radiation, rainfall and all those that act as a primary source of energy.

Usually, the intensity and efficiency of use of these natural resources are not taken into account when assessing sustainability. In this sense, the emergence analysis is a tool, which have allowed to approach the sustainability definition for these guadua forests systems, which is considered in the process of obtaining products, the flow of the resources on which it depends.

The emergy analysis allows quantifying the energy inputs and outputs, as well as evaluating the behavior of the system in terms of the transformation of available energy (Odum, 1996). The emergy flow is related to the "Emergent Memory", which was described previously by Odum (1996), as the useful energy (exergy) of a certain type, which has been used directly or indirectly in the processes of generating a good or service. Emergy analysis evaluates the system components and unifies them under the same measurement (EmJoules) in terms of energy by quantifying the value of biotic and abiotic resources as well as economic resources throughout the production of a good or service (Odum, 1996).

The Emergy analysis has been used to evaluate bamboo plantations (*Dendrocalamus giganteus Munro.*) and has shown to have high input dependence, which makes it unsustainable (Bonilla, Guarnetti, Almeida & Giannetti, 2008).

Based on the above mentioned and in order to carried out a sustainability approach of the guadua (*G. angustifolia*) forests in terms of the energy transformation, this research aimed to calculate the sustainability throughout the emergy analysis in a guadua producing farm located in the Colombian coffee region.

Material and methods

Study area

During this study, was used information from the Yarima Farm, where operates a guadua production company. The farm is located at south of the municipality of Pereira-Risaralda, Colombia and has 24.8 ha in natural guadua forests certified under the FSC standard (FSC- Forest Stewardship Council, 2012), which is located at an elevation of 1200 m.a.s.l., with an average temperature of 22°C and an annual rainfall of 2000 mm (Camargo, Montoya & Quintero, 2014). The area in guadua forests is divided into three stands as follows: 10.4 ha, 6.9 ha and 10.9 ha, respectively. The company has as sale target the guadua culm pieces of 6 m in length, from which two guadua are obtained per culm in average. In this research was established in the farm the average harvested per year is 840 culms.ha^{-1}, representing about 1680 culm pieces. Depending on the market requirements, these pieces are preserved by the immersion method in a solution of boron salts. However, for the purposes of this study, the reference product unit was a 6-meter unassembled culm piece (rounded).

Characteristics associated to the guadua forest management

In the case of this farm, an average of 18% of culms considered as mature and approximately 5 years old, are harvested. Each culm has average dimensions of 22.7 m in length and 11.1 cm width. In fact, each culm are obtained on average from two commercial pieces of 6 m. The remaining pieces are used inside the farm for different purposes, such as fences and crop tutors.

Emergetic analysis

For the emergy analysis, the material and energy flows involved in the process of producing pieces of guadua were identified. The information on the utilization process of guadua forests was collected in field conditions according to the requirements of the methodology proposed by Odum (1996).

Given these concerns, in order to account the flow of matter and energy in the guadua system, it is important to note the use of transformity factor, which represents the equivalent solar energy needed to produce a July (1J) of a product or service (Odum, 1996). The emergia evaluation is obtained by multiplying the value of the matter and/or energy for each input by its respective transformation.

The resources taken into account for a total emergy [Y] evaluation are related with the origin of the same. Renewable natural resources such as rain, wind, solar radiation are represented by the letter R [R]. Non-renewable local resources by the letter N [N], both represent the contribution of nature [I]. The inputs from the human economy such as input labor by the letter F [F], which includes materials [M] and services [S] (Brown & Ugliati, 1997) (Figure 1).

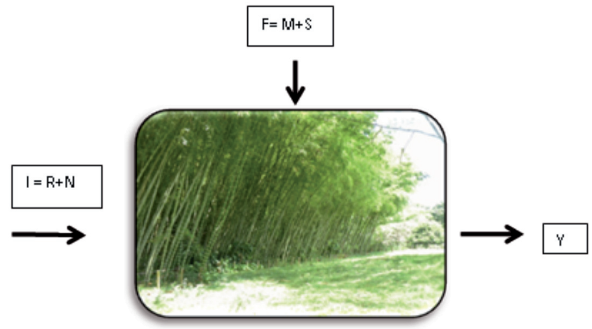


Figure 1. Basic diagram of the flows of matter and energy for guadua production.

For guadua forest system evaluation, the emergy analysis uses sustainability indexes developed by Odum (1996) (Table 1). Under this approach, sustainability is defined with respect to the quantity and quality of energy transformed into a particular production process. Each index describes the components of the system or process and relates them to the other components (I, R, N, F, M, S, Y, respectively).

Table 1. Flows and indices used in emergetic analysis

Symbol	Description	Equation
I	Nature Contributions: Relates Natural Resources (R) with Local Natural Resources (N)	$R + N$
R	Renewable Natural Resources: all those from the environment such as rain, wind, among others	
N	Non-Renewable Natural Local Resources: they come from the study area and are depleted, such as soil or biodiversity.	
F	Feedback from the economy: represents the purchased inputs and services	$M + S$
M	Purchased materials for system operation	
S	Purchased services or used for system operation	
Y	Total Emergy, which is the sum of all inputs into the system.	$I + F$
Tr	Transformicity, the system emergy divided into the total output energy	$\frac{Y}{E}$
%R	Renewability percentage, refers to the value of renewable resources entering into the system divided by total emergy value.	$100\times\frac{R}{Y}$
EYR	**Emergy Yield Ratio:** An indicator of the ability of systems to exploit their local resources. It is measured by dividing the value of the total emergy (Y) over the total value of the purchased inputs (M + S).	$\frac{Y}{F}=\frac{R+N+F}{M+S}$
EIR	**Emergy Investment Ratio:** is an indicator that refers to the fraction of emergy that comes from the natural resources bought divided by the sum of purchased natural resources.	$\frac{F}{(R+N)}$
EER	**Emergy Exchange ratio:** This index relates the product emergy divided by the emergy obtained from the economy. It is an index which shows that so many emergy units are delivered in a product and how much emergy is received in return. It is an equality index.	$\frac{Y}{(\frac{SeJ}{\$})}$
ELR	**Environmental Loating Ratio:** an indicator of the pressure on local ecosystems, or the stress of the ecosystem due to their productive activity. Its value assesses the relationship between purchased resources and non-renewable resources. A high ELR rate means that there is an emergy flow from human activities that carries a heavy load on the system. The sum is calculated as local non-renewable natural resources (N) plus natural resource services and materials (R).	$ELR=\frac{F+N}{R}$
EIS (SI)	**Emergy Sustainability Index:** an indicator of system sustainability, which shows the relationship between performance in terms of emergy and the environmental burden of the system. This index determines that the ideal is for a system to have a high performance index and a low environmental load index.	$SI=\frac{EYR}{ELR}$

Source: Ortega, Anami & Diniz (2002); Odum (1996).

In order to carry out the emergy analysis, the system inputs corresponding to natural resources (solar radiation, rain, wind and evapotranspiration), non-renewable local natural resources (soil), materials and inputs (tools, forest certification, workforce). The information was collected throughout field visits, secondary information and the weather station.

The output corresponding to pieces of 6 m guadua is represented in the systemic diagram using the information previously mentioned (Figure 1). The transformation was calculated taking into account values reported previously in the literature, knowing that it is specific for each product. With the transference values and the inputs/outputs system, we proceeded to calculate the emergy flows or amount of energy used in the system to later calculate the indices which are listed in Table 1.

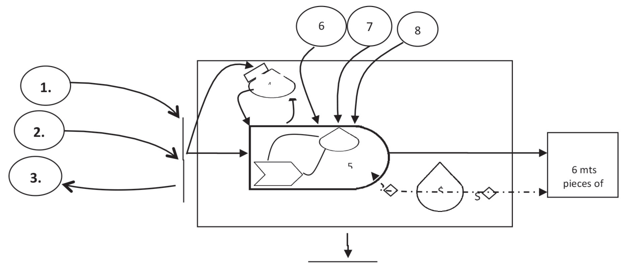
Results

Description of the production process

In a guadua forest, the management activities are divided into three phases. The first includes activities that represent inputs to the system and are associated with guadua forest maintenance, which requires purchased labor and inputs as gasoline and machinery, among others. The second is associated with the culm harvest, which requires labor, machinery and transportation of harvested material (culms). The final phase includes pre-industrial activities, which are performed for the preservation, drying and storage of unprotected culm pieces, which are addressed to the market.

The rain was considered a factor for the emergy evaluation. In fact, daily values of rainfall were obtained from the meteorological station installed by the Risaralda Department Hydroclimatological Network (REDH). The annual average of daily values (REDH, 2014) was used. From the meteorological station also was obtained information on solar radiation, which represents the amount of energy available from the sun to plants to carry out photosynthesis process. Likewise, potential evapotranspiration was included, which is associated with water availability for plants (Komatsu, Onozawa, Kume, Tsuruta, Kumagai, Shinohara & Otsuki, 2010) and from which, in this analysis, represents the required amount of energy for the molecules to pass from liquid to gaseous state (Brooks, Folliott & Magner, 2012). The value in this study is associated with evapotranspiration, which was taken from a previous study (Piouceau, Panfili, Bois, Anastace, Dufossé & Arfi, 2014).

The materials and services within the production process were collected throughout an interview with the guadua producer, among which, labor and inputs are important due to the cost they represent as well as the amount of energy required for their management and/or operation. In the same way, voluntary forest certification (FSC, 2012), which implies a greater work commitment (energy expenditure) as well as a money expenditure, which must be invested in the system to generate the product, plays a fundamental role to determine the guadua forest management and the necessary processes to carry them out. Based on the above mentioned, the inputs and outputs of the system were established as reflected in the emergy diagram (Figure 8).



I: (R + N)

(R) 1 - Solar Radiation 2- Water; 3- Evapotranspiration

N-4 Soil; 5- Guadua forest - Product;

F: (M + S) -6- Labor force; 7-scythe-chainsaw; 8- FSC

Y-Product parts of 6 mts Guadua

Emergy analysis

Based on R (climatic variables)system inputs and outputs of the system information, N (soil) and M (inputs and labor) (Table 2), and with information from the literature which have allowed the calculation of the transformity values for each component (R, N, M, S, I, and Y, respectively) (Table 3), providing the result value in EM Joules with which were obtain the indexes, renewability, Emery Yield Ratio (EYR), energy exchange, Emergy Exchange Ratio (EER), Environmental Load Ratio (ELR), Environmental Sustainability Index (ESI) and the ratio of non-renewable / Renewables resources(Table 4).

Table 2. Inputs and Outputs of material and energy from guadua production system

	Inputs	Current Value	Units	Source
	1. Rainfall	2.45	$m^3.ha^{-1}.year^{-1}$	REDH, 2014
[R]	**2. Solar Radiation**	Max: 1102.33 Min: 283.40	$W.m^{-2}$ $W.m^{-2}$	REDH, 2014
	4. Evapotranspiration	0.34	$mm.day^{-1}$	Piouceau *et al.*, 2014
[N]	**5. Soil**	2.365.883	$Kg.ha^{-1}$ at 30 cm soil depth	Camargo *et al.*, 2014
	6. Labor	$967.74	$US\$.ha^{-1}.year^{-1}$	Yarima Guadua
[M]	**7. Inputs Scythe - chainsaw**	$11.93	$US\$.ha^{-1}.year^{-1}$	Yarima
	8. Fuel	$ 0.20	$US\$.ha^{-1}.year^{-1}$	Yarima

Source: Own elaboration based on REDH, 2014; Camargo *et al.*, 2014

Table 3. Emergy analysis for guadua production

Annotation	ITEM	Unit	Data (Units. year^{-1})	Solar Unit EMERGY (sej.unit^{-1})	Emergy Solar (Sej.year^{-1})
	Recursos Naturales – R				
1	Radiation	J	6.62E+15	1	3.62E+05
2	Rainfall	J	5.34E+13	1.80E+04	9.61E+06
3	Evapotranspiration	J	1.52E+07	1.54E+04	2.34E+01
	Non- Renewble resources – N				
4	Net Loss of Soil	J	6.57E+10	7.38E+04	4.58E+05
	I- Inputs addition- R +N				1.01E07
	Operacional inputs – supplies – M				
5	Fuel	J	3.41E+08	6.60E+04	2.25E+03
6	Equipment	$	5.54E+04	6.06E+04	3.36E-01
7	Labor	$	5.97E+10	6.06E+4	3.61E+05
	Services – S				
8	FSC Certificate	$	2.66E+06	6.06E+4	1.61E+01
	F- Addition of the outputs M+S				3.64E+05
	Total Emergy - Y				1.05E+07
	Calculated Transformity				
9	Transformity	J	4.84E+02	2.33E+17	2.33E+17

Source: Own elaboration based on the template Emergy Evaluation Agriculture Production; Brandt-Williams, 2002.

Table 4. Emergy rates based on the flows of matter and energy for guadua production system

Rates	Formula	Value
% Renewability	$\frac{R}{Y}\times 100$	91.88
Energy Efficiency Rate EYR	$\frac{Y}{F}$	28.75
Energy Exchange Rate EIR	$\frac{(R+N)}{Y}$	0.04
Emergy Exchange Ratio EER	$\frac{Y}{(\frac{Sej}{\$})}$	1.00
Environmental Load Ratio ELR	$\frac{F+N}{R}$	0.09
Environmental Sustainability Index ESI	$\frac{EYR}{ELR}$	325.49

Discussion

Emergetic analysis (Based on the proposed methodology and adapted from Giannetti (2012))

Emergy Yield Ratio EYR: the production index whose value was 28.75 and indicates there is a high energy yield supported mainly in natural resources.

Emergy Investment Ratio EIR: the investment index was 0.04 indicating the amount of purchased (F) energy, which does not exceed the energy coming from the system (I) and therefore, represents the efficiency of the same. Values greater than 1, indicates more dependence on purchased resources.

Emergy Exchange Ratio EER: the value obtained was exactly 1, which indicates that for each energy unit delivered to a consumer, a unit of energy is being received. In this case, the index reflects equality in emergent terms, which is considered optimal.

Environmental Load Ratio ELR: Shows the potential generated environmental impact, which is linked to non-renewable sources of emergy with renewables resources. The result obtained from 0.09, indicates the system is subject to relatively low environmental loads and shows the use of external inputs is small, compared to the resources used.

%Renewability: represents the renewability ability of the analyzed system. The value obtained of 91.88%, indicates in emergetic terms, the proportion of renewable resources on which the product depends. This shows that its possibility of renewal is high as is dependent on 90% of renewable resources.

Environmental Sustainability Index ESI: is based on the premise that sustainability is a function of performance, renewability and environmental burden (Odum, 1996). This index had a value of 325, which can be translated into a highly renewable resource and can be exploited if the characteristics of the system are preserved, but it shows a highly vulnerable system due to its great influence of natural resources.

Emergy from forest and guadua systems

The values found in the indexes, show a system that does not depend on the external inputs under the evaluated site and productivity conditions. However, they show the system could be vulnerable to a possible change or deterioration of the natural resources, which are the major support. This implies that it is necessary to ensure proper handling in order to keep the system in the best state. However, not all resources can be guaranteed or controlled (e.g., rainfall) and this is why the system vulnerability is high. On the other hand, the scale of production that is related to the intensity with which the guadua forest is used, should be maintained despite the fact that the financial indicator qualifies the system in the limit (with a value of 1). Although there is no scientific literature on managed guadua forests, those systems where environmental conditions are better due to the incorporation of trees (Correa *et al.*, 2008), or to maintain forest cover (Ferreira *et al.*, 2010) or bamboo plantations (Bonilla *et al.*, 2008). In the case of guadua forests, Camargo *et al.* (2012), they have found their contribution to different ecological functions such as soil protection and biodiversity. Guadua forests do not represent an agroforestry system, however, they fulfill important functions such as water regulation, carbon sequestration, conservation of biodiversity, among others (Camargo *et al*., 2012) and these characteristics do not represent an inconvenience for their proper management and exploitation. In the same way, Bonilla *et al*. (2008), carried out emergent analyzes in bamboo forests to know the behavior of these forests in front of the management and in terms of sustainability, the results determined that, as in the case of agroforestry systems, resource inflows of natural resources, which contributed to 26% of the total emergy while 16% of emergy, corresponded to workforce. In the present study, guadua forests were found to be sustainable due to a highly dependence (ESI> 1) on renewable natural resources, and had achieved a low environmental burden (ELR <1), given their low dependence on the purchased resources.

System sustainability

The definition of sustainability includes time among its factors. A system is sustainable when, over a set period of time, its performance is maintained under current management conditions (Ulgiati & Brown, 1998). There are several criteria which defines the sustainability or not of a system as follows: total yield process, environmental burden of the process and the use of renewable resources. If a process is underperforming, it will require a continuous energy investment outside the system, which would make it unsustainable (Odum, 1996). In the same way, if it relies heavily on nonrenewable resources, it will be unsustainable and finally if it depends only on renewable resources but generates a high environmental burden, which will be unsustainable (Ulgiati & Brown, 1998).

The renewability index, showed high values due to the emergy proportion which comes from renewable resources. This is evident in the guadua forest behavior under management, which shows a suitable response to the prevailing management conditions and have allowed a sustained harvest of 840 culms.ha^{-1} each year (Camargo, Montoya & Quintero, 2014). This volume is obtained with a low level of external inputs and non-renewable resources. This provides more accurate and reliable estimates of how guadua forests are resources which are usable and are emergy efficient, as long as they are properly managed.

Conclusions

The emergy analysis have allowed to evaluate the sustainability of guadua forest system managed to obtain commercial culms. In fact, the obtained indices showed values which evidenced a low dependence of external inputs without compromising the obtained product. However, these values also describe a vulnerable system to changes in renewable natural resources, especially those which cannot be controlled (e.g., climate). This condition of sustainability also implies sustaining the management of the present intensity and specific conditions of these forests, which, with important dynamics, respond adequately to the harvest levels presented on the farm, guaranteeing a high system renewability.

Environmental sustainability is a positive indicator for the system and represents an important advance in sustainability definition of the guadua forests. The emergy analysis, requires a correct interpretation since they are not universal, they behave in a static way for each analyzed system as long as the conditions in which the measurements were carried out are maintained.

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