19

Emergy Evaluation of Biofuel Production from Water Hyacinth Biomass: Case Study of a Sub Region of Pantanal, Brazil

Luz S. Buller, Enrique Ortega and Ivan Bergier

ABSTRACT

The fast pyrolysis of aquatic macrophytes biomass (e.g. water hyacinth) naturally produced in the Pantanal was assessed through the emergy methodology applied to the whole productive chain including biomass growth in the floodplain, its harvesting in the mainstream river and industrial conversion into bio-oil, liquids and charcoal. Three analysis were performed in order to evaluate the influence of additional services and externalities in the emergy indicators: (a) the first analysis was a traditional emergy evaluation without the accounting of financial fluxes and externalities, (b) the second included fees and an externality assumed as a reserve financial fund of 1% of the total investment and (c) the third included the financial fluxes to acquire equipment and an externality assumed as a reserve financial fund of 5% of the total investment. In analysis (a) the Renewability of 87% showed that the process is sustainable and the Emergy Yield Rate of 3.3 indicated that the process can contribute to the regional economic development. The inclusion of financial fluxes and externalities reduced the Renewability and the Emergy Yield Rate, also increased the Environmental Loading Ratio and the Emergy Investment Ratio. Through the analysis (b) and (c) it could be possible to obtain a broad vision due to the inclusion of significant forces that define the industrial system and that are not considered in traditional emergy analysis.

INTRODUCTION

Current research on renewable energy considers aquatic biomass among several potential sources for biofuel production (Bastianoni et al., 2008; Bhattacharya and Kumar, 2010; Bergier et al., 2012). The sustainability of biofuels requires a system analysis considering environmental, social and economic trade-offs and the dependence on fossil resources including fertilizers, agrochemicals and machinery (Cavalett and Ortega, 2010).

In the Pantanal, an alternative for renewable energy production is the management of the plentiful aquatic biomass naturally existing in the region. These resources can substantially contribute to reduce the local dependence on fossil energy and outsourced materials, meanwhile contributing for the flourishing of a new renewable economy (Bergier et al., 2012). Fast pyrolysis could be a promising approach to convert dried biomass of water hyacinth into useful and valuable products (Luengo, 2011; Bergier et al., 2012). Bio-oil derived from fast pyrolysis can be converted into higher energy content forms such as syngas (Bridgwater, 2012) which is a gas mixture rich in H_2 and CO, whereas the charcoal could be used as soil fertilizer and soil amendment and it is also possible to produce charcoal bricks obtained from the compression of both bio-oil and charcoal or charcoal alone.

The emergy assessment presented in this article was done for a compact pyrolysis plant with processing capacity of 1000 kg h^{-1} dry biomass that has as output 300 kg h^{-1} of bio-oil and 400 kg h^{-1} of charcoal.

Pantanal wetland and aquatic macrophytes

Pantanal is part of the Upper Paraguay Basin that, in turn, is part of the La Plata basin which extends over five countries in the southern continent. The hydrological regime is characterized by a monomodal seasonal flood pulse related to the low relief slope in the floodplain ranging from 0.3 to 0.5 m km^{-1} from East to West and 0.03 to 0.015 m km^{-1} from North to South (Gonçalves et al., 2011). Aquatic macrophytes develop sorely in Pantanal as a result of the main ecological service of wetlands related to nutrient filtering and water quality improvement (Mitsch et al., 2009). Free floating mats of this vegetation growing in marginal lakes, flooded areas, and riverbanks eventually detach and are carried downstream by the Paraguay River. The main species present in the floating mats, superior to 70 %, are *Eicchornia crassipes* and *E. azurea* (Castro et al., 2010), known as water hyacinth. A fraction of the free floating mats that flows downstream the Paraguay River could be collected and processed with appropriate technologies that ensure minimum interference in the natural ecosystem and that contribute to the sustainable socioeconomic development in the region (Bergier et al., 2012; 2008; Berger and Salis, 2011).

The quantity of floating mats that can be removed from the river should rely on the knowledge of its biogeochemical, hydrological and ecological roles in the ecosystem (Bergier et al., 2012). The efficiency in planning and executing economic activities, e.g. extraction and fishery in wetlands, can be supported by parameters predictions like vegetation growth and biogeochemical cycles correlated with the flood-pulse (Schöngart and Junk, 2007). The harvesting level to fulfill the capacity of a compact fast pyrolysis plant is less than 1% of the total aquatic biomass that annually flows in the Paraguay River (Buller, 2012). For higher processing capacities, an ecological approach is required to enlighten the ideal harvest level based on “Ecohydrology” concepts, i.e., a systemic integration between biotic and abiotic factors of aquatic ecosystems to assure that human interferences and ecosystem management are focused on the ecosystem resilience and the long-term sustainability (equilibrium) of the ecosystem “harvest” practices (Zalewski, 2010; 2000).

Fast Pyrolysis of Water Hyacinth Biomass

Tests of fast pyrolysis of water hyacinth biomass showed the technical viability of this resource to obtain fuels and chemical materials of higher aggregated value (Luengo, 2011). The theoretical energy balance of water hyacinth pyrolysis, considering solar drying of the biomass, demonstrates that: (a) bio-oil energy efficiency is 34% (bio-oil higher heating value, HHV, is 15.9 MJ kg^{-1}), (b) charcoal energy efficiency is 24% (HHV 8.4 MJ kg^{-1}) and (c) combustible gases energy efficiency is 42% (HHV 6,6 MJ/kg); where wet biomass of water hyacinth HHV is 14.1 MJ kg^{-1}, the total primary energy input (biomass plus electric power) for a compact fast pyrolysis plant (1000 kg h^{-1}) is 14202 MJ. The electric power consumption is low because the combustible gases are used to feedback energy to the pyrolysis plant, also of the total inflow of biomass a little part is converted into flue gases.

In its natural form, water hyacinth presents 92.2 ± 3.5% (n = 20) humidity and part of this humidity is not linked to the plant tissues and fibers (Luengo, 2011). Then this characteristic enables the use of grinding and compacting equipment to densify the biomass and expunge residual water that may reduce by up to 50% of the total humidity. Solar drying is possible in locations where the air humidity is relatively low and temperature is high, as is the case of the Pantanal floodplain (Luengo, 2011). Different locations require the use of continuous dryers to reduce the humidity from 50% to 10% with a mean energy consumption of 2.9 MJ/kg, which can also be recovered from steam and other hot gases from the pyrolysis process.

MATERIAL AND METHODS

Study area

The study area, Figure 1, was delimited with the extension of 17948.5 km² by Souza et al. (2011). This work evaluated the inter-annual variability of aquatic vegetation coverage in the floodplain for the

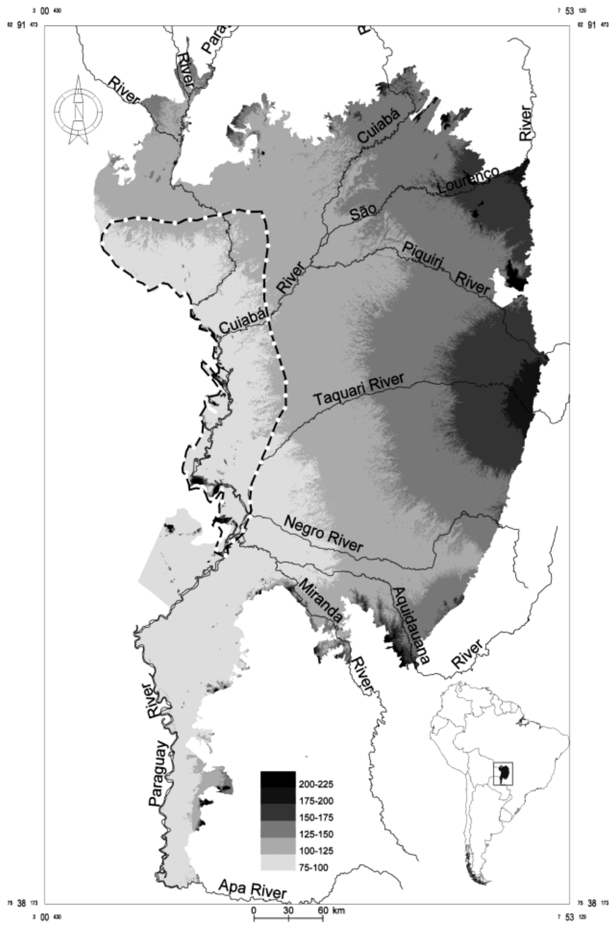

Figure 1. *Topographic gradient of the Pantanal wetland measured with NASA/SRTM (Shuttle Radar Topography Mission); the area outlined with a dashed line corresponds to the river floodplain in 100 to 125 meters asl (above sea level) in Brazil.*

time period from 1987 to 2009 to identify areas permanently occupied; areas that assuredly provide aquatic vegetation to the river even for dryer years. In case of making use of a fraction of that biomass transported by the river, these areas should be considered as hotspot sites for natural preservation.

Biomass production system

Figure 2 shows the ecological relationships of water hyacinth with the food web and the nutrient cycling. It is important to note that the nutrients inflow is seasonal and dependent on the magnitude and duration of the water pulse triggered in the upper part of the basin. A simplification of the biomass growth model is that the system produces three ecological services or outputs: aquatic vegetation biomass, fish and cleaner water (due to nutrient removal caused by vegetation growth).

The biomass produced during the flood and the dry periods was estimated over the area occupied by aquatic vegetation biomass considering its variability over 17 years (Buller, 2012). Phosphorous loading in the study area was estimated as the contribution of Paraguay River's main tributaries. Phosphorous incorporated into water hyacinth biomass was estimated from the biomass chemical. A mass balance considering the phosphorous distribution in the system (inflow, biomass removal, detritus conversion, sediment releases) provided an estimate of the quantity of phosphorous in the water column accordingly to the seasonal floodplain pulsing of the Paraguay River (Buller, 2012).

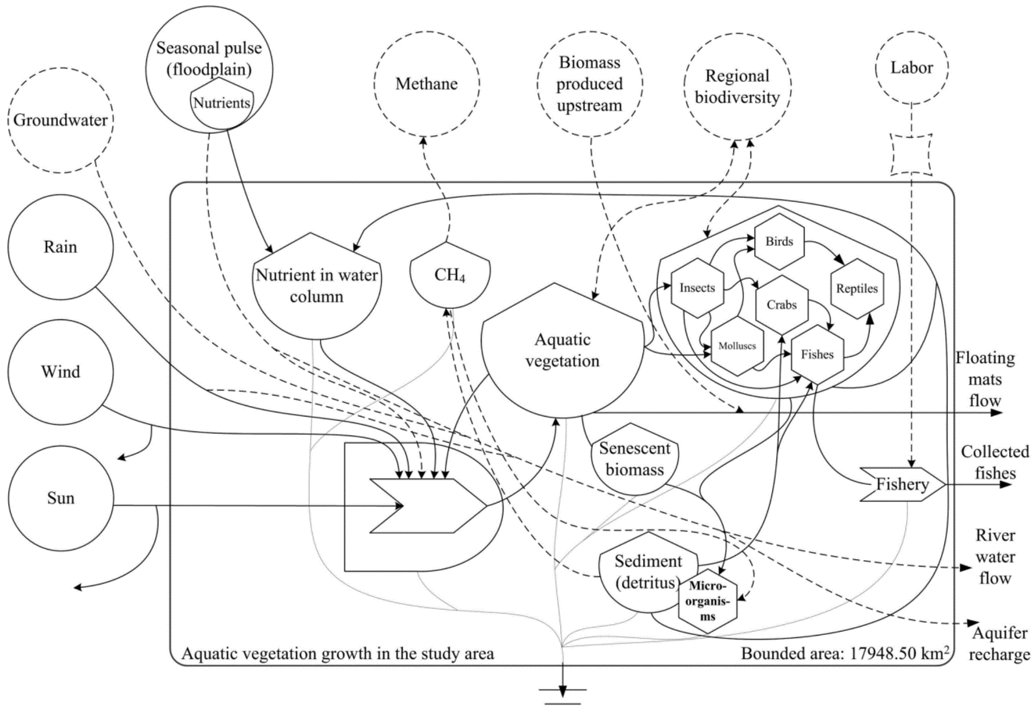

Figure 2. *System diagram of aquatic vegetation biomass growth.*

A previous emergy assessment provided the biomass transformity applied in the further biomass conversion emergy assessment. The complete biomass production emergy assessment can be found in Buller et al. paper entitled "Water Hyacinth Biomass Valuation Using Emergy" presented in this volume of the Proceedings of the Seventh Biennial Emergy Conference.

Biomass harvest and fast pyrolysis processing

Figure 3 diagram considers material inputs, external services and financial flows needed to collect or to harvest biomass flowing river downstream. The equipment to carry out the biomass harvest in the river could be composed of crawlers, steamroller and rotating knives to collect the floating mats, remove water in excess and reduce leaves and roots to suitable sizes for processing. The drying of biomass considered here is the use of solar energy which is considered a suitable method for the compact pyrolysis plant full demand in the study region.

Fast pyrolysis process is presented in Figure 4. The destination of the industrial products could be in three different ways: bio-oil gasification to produce syngas (which is feasible in large-scale production), charcoal for soil fertilizer production or coal bricks production.

Emergy assessment for biomass harvesting and industrial processing

Three different evaluations were performed for the industrial system in order to include the influence of additional services and externalities in the emergy assessment of fast pyrolysis outputs, bio-oil and biocharcoal. The externalities could be heat, gaseous emissions, solid wastes and effluents represented as the inclusion of the necessary money to be designated to manage and/or avoid environmental and social damages derived of the industrial operation.

All calculations and assumptions related to the emergy assessment of water hyacinth biomass fast pyrolysis are shown in Appendix. The evaluations are relative to a pyrolysis plant able to process 1000 kg h^{-1} of dried biomass from aquatic vegetation.

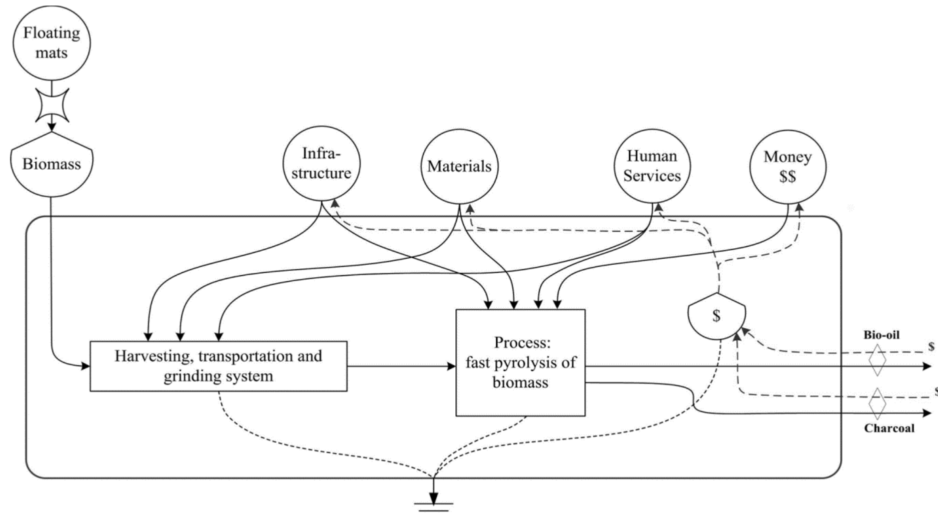

Figure 3. *System diagram of aquatic vegetation biomass harvest and industrial processing.*

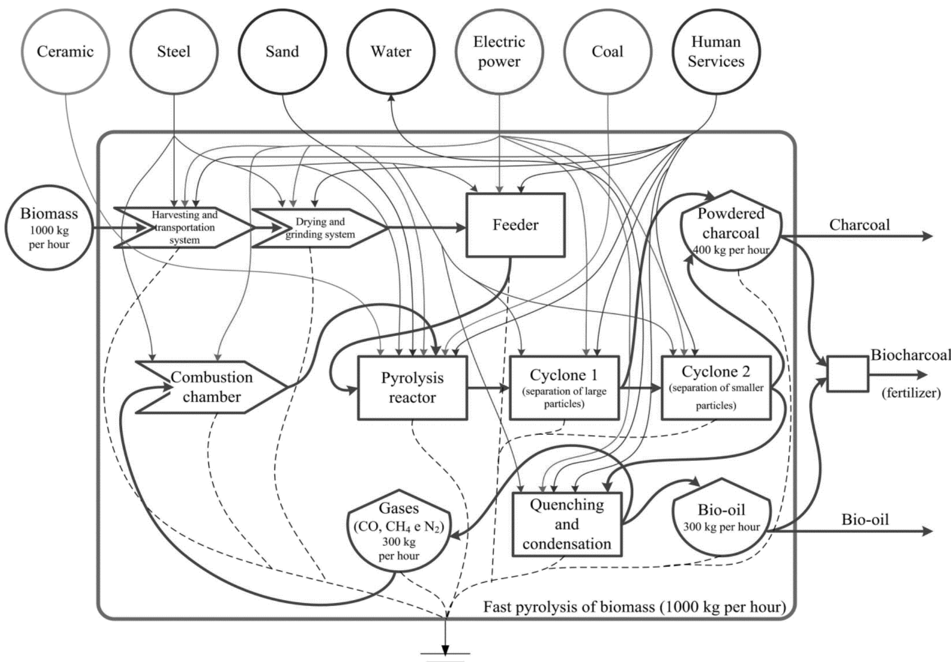

Figure 4. *System diagram of fast pyrolysis of biomass.*

Table 1 shows all the emergy flows for biomass harvesting and processing. The first analysis (Table 1) follows the traditional emergy evaluation proposed by Odum (1996) including the modified methodology proposed by Ortega et al. (2005). The difference in second analysis (Table 2) is the inclusion of governmental taxes and fees and an externality factor assumed as a reserve financial fund of 1% of the total investment. At last, the third analysis (Table 3) includes the financial fluxes to acquire the equipment for industrial processes and an externality factor assumed as a reserve financial fund of 5% of the total investment. The financial funds values are authors' *ex-ante* estimations applied to enlarge the analysis framework once the fast pyrolysis equipment supplier does not have an *ex-post* analysis for the pyrolysis plant operation.

Table 1. Annual emergy flows for industrial system, analysis 1.

	Inputs	Flow	Unit	UEV (seJ unit^{-1})	Reference	Emergy (seJ year^{-1})	%	Emergy (Em$ year^{-1})	Renew-ability index	Renewable emergy (seJ year^{-1})	Non-ren. emergy (seJ year^{-1})
	Renewable – R					**5.70E+17**	**69.7**	**4.83E+04**		**5.70E+17**	**0.00E+00**
R1	Aquatic vegetation biomass	2.93E+13	J year^{-1}	1.65E+04	Biomass production emergy evaluation	4.83E+17	59.1	4.10E+04	1	4.83E+17	0.00E+00
R2	Water (to the quenching system, obtained from the river)	1.17E+11	J year^{-1}	6.22E+05	Biomass production emergy evaluation	7.24E+16	8.9	6.14E+03	1	7.24E+16	0.00E+00
R3	Coal (pre-heating)	5.65E+09	J year^{-1}	1.41E+06	Alonso-Pippo et al., 2004	7.95E+15	1.0	6.74E+02	1	7.95E+15	0.00E+00
R4	Sand	3859	kg year^{-1}	1.68E+12	Odum, 1996	6.48E+15	0.8	5.49E+02	1	6.48E+15	0.00E+00
										MR	**MN**
	Economic Materials - M					**1.38E+17**	**16.8**	**1.17E+04**		**6.21E+16**	**7.56E+16**
M1	Steel for building	336	kg year^{-1}	4.65E+12	Haukoos, 1995	1.56E+15	0.2	1.32E+02	0	0.00E+00	1.56E+15
M2	Cement for building	436	kg year^{-1}	2.02E+12	Haukoos, 1995	8.81E+14	0.1	7.47E+01	0	0.00E+00	8.81E+14
M3	Steel (Harvesting and grinding system)	700	kg year^{-1}	4.65E+12	Haukoos, 1995	3.26E+15	0.4	2.76E+02	0	0.00E+00	3.26E+15
M4	Steel (Feeder and reactor)	402	kg year^{-1}	4.65E+12	Haukoos, 1995	1.87E+15	0.2	1.58E+02	0	0.00E+00	1.87E+15
M5	Steel (Cyclones)	16	kg year^{-1}	4.65E+12	Haukoos, 1995	7.48E+13	0.0	6.34E+00	0	0.00E+00	7.48E+13
M6	Steel (Bio-oil recovery system)	67	kg year^{-1}	4.65E+12	Haukoos, 1995	3.12E+14	0.0	2.64E+01	0	0.00E+00	3.12E+14
M7	Steel (Bio-oil & biocharcoal collection system)	39	kg year^{-1}	4.65E+12	Haukoos, 1995	1.81E+14	0.0	1.53E+01	0	0.00E+00	1.81E+14
M8	Steel (Combustion chamber)	32	kg year^{-1}	4.65E+12	Haukoos, 1995	1.50E+14	0.0	1.27E+01	0	0.00E+00	1.50E+14
M9	Ceramic	1005	kg year^{-1}	5.14E+12	Brown and Buranakarn2003	5.17E+15	0.6	4.38E+02	0	0.00E+00	5.17E+15
M10	Electric power	1.11E+12	J year^{-1}	1.12E+05	Brown and Ulgiati, 2004	1.24E+17	15.2	1.05E+04	0.5	6.21E+16	6.21E+16
										SR	**SN**
	Human					**1.10E+17**	**13.5**	**9.32E+03**		**7.70E+16**	**3.30E+16**
S1	Specialized labor: 1 technician	9.07E+08	J year^{-1}	4.04E+07	Calculated	3.66E+16	4.5	3.11E+03	0.5	1.83E+16	1.83E+16
S2	Operational labor: 2 maintenance operators	2.18E+09	J year^{-1}	2.53E+07	Calculated	5.50E+16	6.7	4.66E+03	0.8	4.40E+16	1.10E+16
S3	Operational labor: 1 assistant	1.16E+09	J year^{-1}	1.58E+07	Calculated	1.83E+16	2.2	1.55E+03	0.8	1.47E+16	3.66E+15
S4	Mechanical maintenance	1.00E+08	J year^{-1}	6.12E+05	Calculated	6.15E+13	0.0	5.21E+00	0.5	3.08E+13	3.08E+13
	TOTAL EMERGY – Y					**8.18E+17**	**100**	**6.93E+04**		**7.09E+17**	**1.09E+17**

Table 2. Additional items for annual emergy flows for industrial system, analysis 2 with SA and 1% of invested capital as fund reserve for externalities.

	Inputs	Flow	Unit	UEV (seJ unit^{-1})	Reference	Emergy (seJ year^{-1})	%	Emergy (Em$ year^{-1})	Renew-ability index	Renewable emergy (seJ year^{-1})	Non-ren. emergy (seJ year^{-1})
	Additional Services - SA									**SR**	**SN**
S7	Taxes and fees (value calculated according to Brazilian laws)	82101	U$ year^{-1}	1.18E+13	Sweeney et al., 2008	9.69E+17	50.5	8.21E+04	0	0	9.69E+17
	Externalities	11105	U$ year^{-1}	1.18E+13	Sweeney et al., 2008	1.31E+17	6.8	1.11E+04	0	0	1.31E+17
	Gaseous emissions of industrial plant										
	Solid waste of production										
	Effluent										
	TOTAL EMERGY – Y (Including previous items R, M and Services from table 1)					**1.92E+18**	**100**	**1.63E+05**		**7.09E+17**	**1.21E+18**
	EMBODIED EMERGY – Y (to avoid double accounting, the item materials was excluded because it is already included in the financing money flow)					**1.78E+18**		**1.51E+05**		**6.47E+17**	**1.13E+18**

Table 3. Annual emergy flows for industrial system, analysis 3 with SA and 5% of invested capital as fund reserve for externalities.

	Inputs	Flow	Unit	UEV (seJ unit^{-1})	Reference	Emergy (seJ year^{-1})	%	Emergy (Em$ year^{-1})	Renew-ability index	Renewable emergy (seJ year^{-1})	Non-ren. emergy (seJ year^{-1})
	Additional Services - SA									**SR**	**SN**
S5	Payment of main capital of financing	111048	U$ year^{-1}	1.18E+13	Sweeney et al., 2008	1.31E+18	33.4	1.11E+05	0	0	1.31E+18
S6	Payment of interests over financing	14325	U$ year^{-1}	1.18E+13	Sweeney et al., 2008	1.69E+17	4.3	1.43E+04	0	0	1.69E+17
S7	Taxes and fees	82101	U$ year^{-1}	1.18E+13	Sweeney et al., 2008	9.69E+17	24.7	8.21E+04	0	0	9.69E+17
	Externalities	55524	U$ year^{-1}	1.18E+13	Sweeney et al., 2008	6.55E+17	16.7	5.55E+04	0	0	6.55E+17
	TOTAL EMERGY (Including previous items R, M and Services from table 2)					**3.92E+18**	**100**	**3.32E+05**		**7.09E+17**	**3.21E+18**
	EMBODIED EMERGY – Y (to avoid double accounting, the item materials was excluded because it is already included in the financing money flow)					**3.78E+18**		**3.21E+05**		**6.47E+17**	**3.14E+18**

The modified emergy methodology Ortega et al. (2005) was adopted in this work. It differs from the traditional method Odum (1996) by the inclusion of partial renewability in emergy flows calculations considering renewable and non-renewable fractions of materials and human services. The modified methodology evidences the influence of significant renewable forces from outside system that are not considered in the traditional calculations.

RESULTS AND DISCUSSION

The emergy flows of the fast pyrolysis outputs are presented in Table 4. The aggregated emergy flows for three different evaluations can be found in Table 5, and also the emergy indicators for each case are presented in Table 6.

Table 4. Outputs emergy flows of fast pyrolysis process evaluation.

OUTPUTS	Flow	Unit	Sales price (US$ kg^{-1})	Produced Amount (kg $year^{-1}$)	Sales (US$ $year^{-1}$)	Sales (seJ $year^{-1}$)
P1 Bio-oil	9.93E+12	J $year^{-1}$	0.55	624000	340364	4.02E+18
P2 Powdered charcoal	7.00E+12	J $year^{-1}$	0.27	832000	226909	2.68E+18

Table 5. Aggregated emergy flows.

Emergy flows	Analysis 1	Analysis 2	Analysis 3	Unit
Renewable natural resources - R	5.70E+17	5.70E+17	5.70E+17	
Non-renewable natural resources - N				seJ $year^{-1}$
Total of Natural Resources – I (I = R + N)	5.70E+17	5.70E+17	5.70E+17	seJ $year^{-1}$
Materials of economy - M	1.38E+17	1.38E+17	1.38E+17	seJ $year^{-1}$
MR	6.21E+16	6.21E+16	6.21E+16	seJ $year^{-1}$
MN	7.56E+16	7.56E+16	7.56E+16	seJ $year^{-1}$
Services of economy - S	1.10E+17	1.08E+18	2.56E+18	seJ $year^{-1}$
SR	7.70E+16	7.70E+16	7.70E+16	seJ $year^{-1}$
SN	3.30E+16	3.30E+16	3.30E+16	seJ $year^{-1}$
Additional services - SA		9.69E+17	2.45E+18	seJ $year^{-1}$
Feedback of economy – F (F = M + S)	2.48E+17	1.22E+18	2.70E+18	seJ $year^{-1}$
Externalities		1.31E+17	6.55E+17	seJ $year^{-1}$
Embodied emergy – Y (Y = I + F)	8.18E+17	1.92E+18	3.78E+18	seJ $year^{-1}$
Unity emergy value – Em$	6.93E+04	1.63E+05	3.21E+05	Em$ $year^{-1}$

Table 6: Emergy indicators of the 3 analyses.

Emergy indicators	Analysis 1: *Without financial flows and externalities*	Analysis 2: *With taxes and fees, as financial flows and capital reserve of 1% of the total investment as externalities*	Analysis 3: *With taxes and fees, financing flows and capital reserve of 5% of the total investment as externalities*
Bio-oil transformity	8.24E+04	1.93E+05	3.95E+05
Biocharcoal transformity	1.17E+05	2.74E+05	5.60E+05
% Renewability	86.72%	36.99%	18.75%
EYR	3.30	1.58	1.40
EIR	0.43	2.13	4.73
ELR	0.15	0.15	0.15
EER – for bio-oil	0.20	0.48	0.98
EER – for biocharcoal	0.31	0.72	1.46

Table 7: Comparison of renewability for bio-oil obtained by fast pyrolysis and other biofuels.

Product	Reference	Renewability (%)
Bio-oil	This work	86.7
Biodiesel	Cavalett and Ortega, 2010	30.7
Ethanol	Pereira and Ortega, 2010	30.9

Regarding the results for the industrial conversion of biomass in pyrolysis products, each indicator is discussed ahead. The Emergy Yield Rate (EYR) obtained in this study, 3.36, shows that the emergy yield for aquatic vegetation biomass processing is high compared to the economic resources used. The Emergy Investment Ratio (EIR) of 0.43 indicates that there is a low demand of economic resources and, because of this, the industrial process can be considered competitive at local level. For this particular study, the Emergy Loading Ration (ELR) reached the outstanding result of 0.15 due to the use of a renewable raw material, aquatic vegetation biomass, river energy, and local labor. This value is close to zero meaning that the impact on the environment is minimal. The Emergy Exchange Rate (EER) obtained for bio-oil and charcoal are, respectively, 0.21 and 0.31. These values mean a net benefit for the pyrolysis plant.

The comparison of the emergy indicators obtained (Table 6) suggested that the inclusion of financial fluxes and externalities in emergy assessment was the factor that reduced the renewability and the EYR and also increased the ELR and EIR. A global analysis of the emergy indicators shows that fast pyrolysis of water hyacinth biomass has a good performance when compared to other biofuels (Table 7). It can be observed through the comparison of the renewability of aquatic biomass bio-oil, soybean biodiesel and sugarcane ethanol that the former is more sustainable. This fact follows from the non-dependence on fossil fuel resources, machinery and fertilizers for the production and transportation of the biomass.

CONCLUSIONS

Regardless of the renewability value obtained in analysis 1 is excellent, bio-oil cannot be used as a combustible directly; it is necessary other industrial process, e.g., gasification, to convert this form to useful fuel. A more conclusive analysis regarding the renewability and sustainability including the gasification of the bio-oil is necessary. It is recommended a complete Life Cycle Assessment (LCA). The analysis 2 and 3 provided different sustainability levels and a possibility to evaluate the industrial process with a broaden vision through the inclusion of relevant forces that define the industrial system and that are not considered in traditional emergy analysis.

The indicators here obtained are preliminary and related to a compact fast pyrolysis plant. Further research is necessary to evaluate with a broader perspective the viability of upscaling the industrial plant that could be installed nearby Corumbá or along the Paraguay River in the Mercosur. Also, to avoid environmental impacts arising from unsustainable biomass exploitation (illegal harvesting of marginal floodplain lakes and river banks, overharvesting of the free-flowing macrophyte mats) it is necessary to develop regulatory mechanisms and public policies to govern and establish monitoring levels of biomass harvesting. Feedback mechanisms over time are demanded and more studies shall be carried out on the food web structure and the functionality of floating mats exported by the Paraguay River to ensure the better and more sustainable biomass-to-biofuel conversion and to ensure the maintenance of eventual downstream ecosystem services provided by these free-floating vegetation mats.

FINAL REMARKS

The inclusion of financial fluxes and externalities in the emergy assessment could be adopted for natural and preserved systems subject to human interference looking for new approaches to ensure the commitment of the investors and governments in a sustainable management and wise use of natural resources for economic growth and social inclusion.

It is recommended the use of the values reported here as the maximum and minimum emergy indicators for the establishment of a harvesting and processing system of aquatic vegetation depending on the origins of the invested capital and on the policies towards the exploitation of a natural resource in Pantanal. The ecological viability to operate one or more compact or scaled-up pyrolysis plants in the hydrographic basin should rely on regional and local regulations to ensure a truly sustainable production involving financial provision mechanisms to manage environmental and social possible impacts derived of the industrial operation.

ACKNOWLEDGEMENTS

This work was partially funded by the Project “Biofuel production from floating biomass mats in Brazilian floodplains: a case study in Pantanal” (MCT/CNPq/CT-Energ52-2008, 578084/2008- 2 and EMBRAPA Macroprograma 2 Infoseg 02.09.00.015.00.00). The authors gratefully acknowledge financial support from the National Council for Scientific and Technological Development (CNPq, Brazil). Special thanks to Luiz Alberto Pellegrin, Embrapa Pantanal, GIS and Remote Sensing Analyst.

REFERENCES

Alonso-Pippo, W., Rocha, J.D., Mesa-Pérez, J.M., Olivares-Gómez, E., Cortez, L.A.B., 2004. Emergy evaluation of bio-oil production using sugarcane biomass residues at fast pyrolysis pilot plant in Brazil, in Ortega, E., Ulgiati, S. (Ed.), Proceedings of the IV Biennial International Workshop Advances In Energy Studies, 2004 Jun 16-19, Campinas, SP, Brazil: Gráfica da Universidade Estadual de Campinas, pp. 401-408.

Bastianoni S., Coppola F., Tiezzi E., Colacevich A., Borghini F., Focardi S., 2008. Biofuel potential production from the Orbetello lagoon macroalgae: A comparison with sunflower feedstock. Biomass Bioenerg 32 (7), 619-628.

Bergier, I., Salis, S.M., Miranda, C.H.B., Ortega, E., Luengo, C.A., 2012. Biofuel production from water hyacinth in the Pantanal wetland. Ecohydrology & Hydrobiology 12, 77-84.

Bergier, I., Ishii, I.I., Salis, S.M., Pellegrin, L.A., Resende, E.K., Tomás, W.M., Soares, M.T.S., 2008. [Sustainable development scenarios in Pantanal according to hydroclimatic tendencies]. Documentos/Embrapa Pantanal [Internet]. p.20. Available at: http://www.cpap.embrapa.br/publicacoes/online/DOC98.pdf [accessed 10.10.10]. Portuguese.

Bergier, I., Salis, S.M., 2011.[Ecosystem surplus and renewability of wetlands production systems]. Documentos/Embrapa Pantanal [Internet]. p.11. Available at: www.cpap.embrapa.br/publicacoes/online/DOC114.pdf [accessed 02.10.12]. Portuguese.

Bhattacharya, A., Kumar, P., 2010. Water hyacinth as a potential biofuel crop., Electronic Journal of Environmental, Agricultural and Food Chemistry, pp. 112-122.

Bridgwater, A.V., 2012. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenerg 38, 68-94.

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour Conserv Recy 38 (1), 1-22.

Brown, M.T., Ulgiati, S., 2004. Emergy analysis and environmental accounting. In: Cleveland, C. (Ed.), Encyclopedia of Energy. Elsevier, New York.

Buller, L.S., 2012. [System modeling of water hyacinth life cycle in Pantanal and analysis of the use of this biomass for bio-oil and bio-fertilizer production] M.Sc. dissertation, State University of Campinas, Campinas. Available at: www.unicamp.br/fea/ortega/extensao/Dissertacao-SeleneBuller.pdf. Portuguese.

Castro, W.J.P., Vianna, E.F., Salis, S.M., Galvani, F., Lima, I.B.T., 2010. [Floristic Composition and Associated Fauna of Free Floating Islands, Rio Paraguay, Corumbá, MS], [Proceedings of the 5th Pantanal natural resources and socioeconomic Symposium]; 2010 Nov 9-12; Corumbá, Brazil. Corumbá: Embrapa Pantanal, UFMS; Campinas: ICS do Brasil; 1 CD-ROM SIMPAN, pp.

Unpaged. Available at: ainfo.cnptia.embrapa.br/digital/bitstream/item/24928/1/sp17256.pdf [accessed 02.07.13].Portuguese.
Cavalett, O, Ortega, E., 2010. Integrated environmental assessment of biodiesel production from soybean in Brazil. J Clean Prod 18 (1), 55-70.
Gonçalves, H.C., Mercante, M.A., Santos, E.T., 2011. Hydrological cycle. Braz J Biol 71Suppl 1, 241-253.
Haukoos, D.S., 1995. Sustainable Architecture and its relationship to industrialized building M.Sc.dissertation, University of Florida, Gainesville.
Luengo, C.A., 2011. (State University of Campinas, Physics Institute, Campinas, BR). [Biofuel production from aquatic floating mats in Brazilian floodplains: case study in the Pantanal]. Final Report. Campinas (SP, Brazil): Group of Alternative Fuels, GCA/DFA/IFGW/UNICAMP. Project MCT/CNPq/CT-ENERG-52 578084/2008-2. Portuguese.
Mitsch, W.J., Gosselink, J.G., Anderson, C.J., Zhang, L., 2009. Wetland Ecosystems. John Wiley, New Jersey, USA.
Odum, H.T., 1996. Environmental Accounting: Emergy and environmental decision making. John Wiley, New York, USA.
Ortega, E., Cavalett, O., Bonifácio, R., Watanabe, M., 2005. Brazilian Soybean Production: Emergy Analysis with an Expanded Scope. B Sci Technol Soc 25 (4), 323-334.
Pereira, C.L.F., Ortega, E., 2010. Sustainability assessment of large-scale ethanol production from sugarcane. J Clean Prod 18 (1), 77-82.
Schöngart, J., Junk, W., 2007. Forecasting the flood-pulse in Central Amazonia by ENSO-indices. Journal of Hydrology, 124-132.
Souza, R.C.S., Vianna, E.F., Pellegrin, L.A., Salis, S.M., Costa, M., Bergier, I., 2011. [Location of permanent area occupied by aquatic vegetation in Paraguay River floodplain and surroundings], [Proceedings of the XV Brazilian Symposium of Remote Sensing – SBSR], 2011 Apr 30- May 5, Curitiba, PR, Brazil. São José dos Campos, Brazil: MCT/INPE; DVD + Internet, pp. 2036-43. Available at: http://www.dsr.inpe.br/sbsr2011/files/p0813.pdf [accessed 02.07.13]. Portuguese.
Sweeney, S., Cohen, M.J., King, D., Brown, M.T., 2008. Creation of a Global Emergy Database for Standardized National Emergy Synthesis, in: Bardi, E. (Ed.), 4th Biennial Emergy Research Conference, 2006 Jan. Center for Environmental Policy, Gainesville, pp. 56-78.
Zalewski, M., 2000. Ecohydrology - the scientific background to use ecosystem properties as management tools toward sustainability of water resources. Guest Editorial. Ecol Eng 16 (1), 1-8.
Zalewski, M., 2010. Ecohydrology for compensation of Global Change. Braz J Biol 70 Suppl 3, 689-695.

APPENDIX

Materials transformities include "labor and services".

Emdollar Brazil	1.18E+13	seJ US$$^{-1}$	Sweeney et al., 2008
Transformity values baseline			Odum et al., 2000
Fast pyrolysis plant operational conditions			
Total hours per year operation	2080	h year^{-1}	
Fast pyrolysis plant production capacity	1000	kg$_{dry\ matter}$ h^{-1}	
Operational team: 1 technician, 2 maintenance operators and 1 assistant			
R1. Aquatic vegetation biomass			
Annual Consumption	2.08E+06	kg$_{dry\ matter}$ year^{-1}	
Biomass energy content	1.41E+07	J kg$_{dry\ matter}^{-1}$	
Energy flow = annual consumption x energy content	2.93E+13	J year^{-1}	
R2. Water			
Annual Consumption	2.36E+04	m³ year^{-1}	

Gibbs free energy	4.94E+03	J kg^{-1}	
Energy flow = annual consumption x energy content x water density	1.16E+11	J year^{-1}	
R3. Coal (quantity only to start the process, this item is obtained from the own pyrolysis process)			
Annual Consumption	643.20	kg year^{-1}	
Coal energy content	8.79E+06	J kg^{-1}	
Energy flow = annual consumption x energy content	5.65E+09	J year^{-1}	
M1 and M2. Building (Authors calculations)			Buller, 2012
Depreciation	25	years	http://www.receita.fazenda.gov.br/legislacao
M3 to M8. Steel for equipments			
Depreciation	10	years	http://www.receita.fazenda.gov.br/legislacao
S1. Specialized Labor			
1 technician energy consumption for work demand	9.07E+08	J year^{-1}	
Technician energy consumption for living, 365 days a year	3.82E+09	J year^{-1}	
Year salary considering taxes and charges	13080	US$ year^{-1}	Buller, 2012
Transformity = year salary x emdollar/(energy consumption for work and living)	4.04E+07	seJ J^{-1}	
S2. Operational Labor			
2 maintenance operators energy consumption for work	2.18E+09	J year^{-1}	
Maintenance operator energy consumption for living, 365 days a year	4.58E+09	J year^{-1}	
Year salary considering taxes and charges	9810	US$ year^{-1}	Buller, 2012
Transformity = year salary x emdollar/(energy consumption for work and living)	2.53E+07	seJ J^{-1}	
S3. Operational Labor	6540		
1 assistant energy consumption for work demand	1.16E+09	J year^{-1}	
Assistant energy consumption for 365 for living, days a year	4.89E+09	J year^{-1}	
Year salary considering taxes and charges	6540	US$ year^{-1}	Buller, 2012
Transformity = year salary x emdollar/(energy consumption for work and living)	1.58E+07	seJ J^{-1}	
S4. Mechanical Maintenance (8 hours/year)			
2 maintenance operators energy consumption for work	1.26E+07	J year^{-1}	
Maintenance operator energy consumption for living, 365 days a year	4.58E+09	J year^{-1}	
Year salary considering taxes and charges	237.82	US$ year^{-1}	Buller, 2012
Transformity = year salary x emdollar/(energy consumption for work and living)	6.12E+05	seJ J^{-1}	
P1. Bio-oil			
Production	300	kg h^{-1}	
Energy	1.59E+07	J kg^{-1}	
P2. Coal			
Production	400	kg h^{-1}	
Energy	8.41E+06	J kg^{-1}	
P3. Combustible Gases			
Production	300	kg h^{-1}	
Energy	2.93E+07	J kg^{-1}	