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Using the Values of Internal Emergy Flows for Emergy Accounting in Agricultural Complex Systems

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ABSTRACT

Most of the emergy analysis studies of agricultural systems found in literature deal with highly simplified systems. As the agricultural systems are complex, it is not trivial to identify the interactions and to account for the internal emergy flows. The integrated production system of grains (soybean, corn and wheat), pig and fish represents an example of complex system yielding co-products.The main objective of this work is to find the most appropriate way to calculate transformity values for such a complex system. In doing so, we used four different methods to calculate the transformities for the investigated system, discussing the accuracy of each method. The following transformities were calculated using the conventional emergy methodology (Odum, 1996): soybean = $2.09x10^6$ sej J^{-1}; wheat = $1.65x10^7$ sej J^{-1}; pig = $2.18x10^6$ sej J^{-1}; fish = $1.66x10^7$ sej J^{-1}. Using the "joint transformity" concept (Bastianoni and Marchettini, 2000) the transformity value calculated for the integrated system resulted in $9.48x10^5$ sej J^{-1}. The transformity values calculated for each subsystem considered separately were: grains (wheat and soybean) = 2.77x105 sej J^{-1}; pig = 2.09x106 sej J^{-1} and fish = 3.04x106 sej J^{-1}. Finally, the transformity values calculated using the eigenvector method (Patterson, 1983; Collins and Odum, 2000; Odum and Collins, 2003) were: grains = $4.37x10^5$ sej J^{-1}; pig = $1.46x10^5$ sej J^{-1} and fish = $2.75x10^6$ sej J^{-1}. Measuring the net of internal emergy flows in a complex system allows calculating the transformity values considering each subsystem separately. The results show that this procedure seems to be the most suitable to calculate the transformities of the integrated production system.

INTRODUCTION

Several efforts have been made in analyzing processes and systems and their related energy flows in order to calculate ecological indicators of complex natural and human-dominated ecosystems. However, this goal is constrained by a deeper understanding of the evaluated systems. The efforts done by Howard T. Odum to define a scientific and quantitative criteria to measure both the work of nature and humans in generating products and services has constituted an important step towards a deeper understanding of environmental systems and their dynamics. Odum (1996) defined the emergy value as the work previously required to generate a product or service.

Energy systems diagrams are used to model real systems, considering matter, energy and money flows and complex transformation processes. However, most of emergy studies of agricultural systems found in literature deal with simplified systems (normally considering only one product). Energy network diagrams are usually highly aggregated, showing only few pathways of matter and energy. In the attempt of considering the complexity of the system, the evaluation of the internal emergy flows is not a trivial task. In doing so, the application of emergy methodology may become more difficult, but it may also provide more accurate indicators. Figure 1 shows the emergy systems

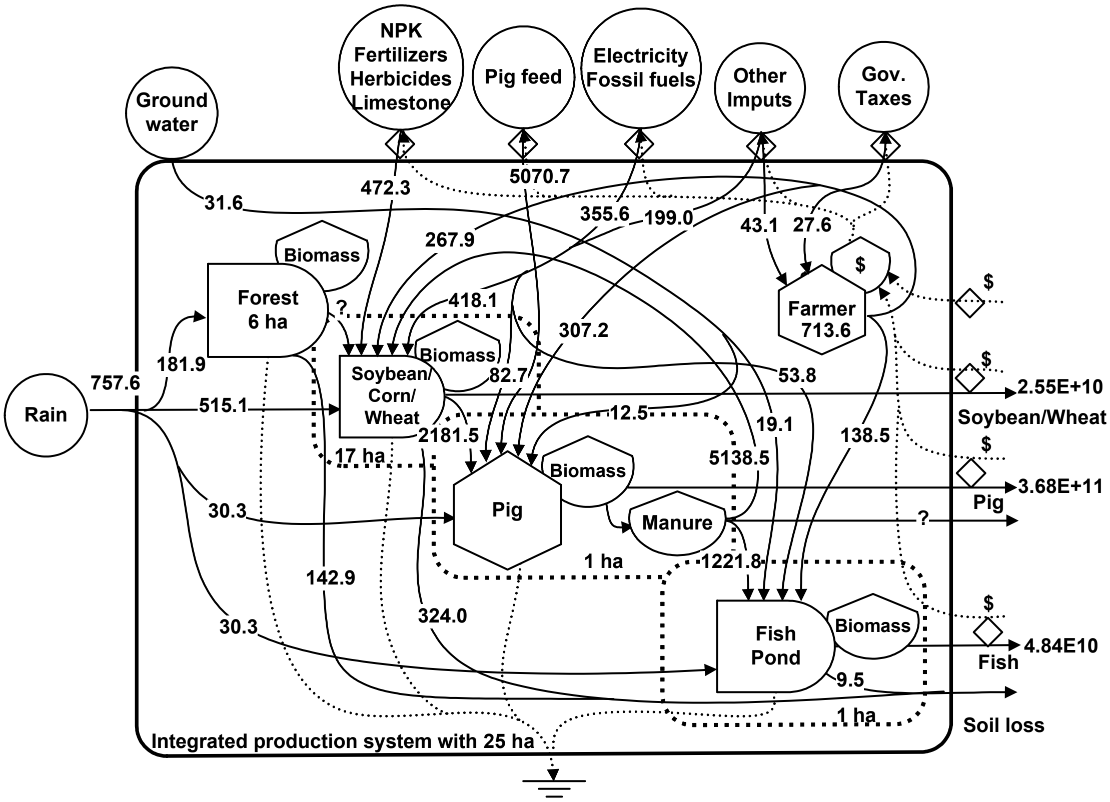

Figure 1. *Emergy systems diagram of the integrated production system of grain, pig and fish. All emergy flows are multiplied by* 10^{14} *seJ year*$^{-1}$*. The outputs (soybean, wheat, pig and fish) are in J year*$^{-1}$ *(Cavalett et al. 2005). Note: grain subsystem produce corn, wheat and soybean, however the outputs are only soybean and wheat because corn is used by pig subsystem.*

diagram of the integrated production system of grain, pig and fish, which is an example of a complex production system yielding co-products.

The aim of this work is to find the more appropriate way to calculate the transformity values for such a complex system by using four different methods:
1. the conventional method (Odum, 1996);
2. the “joint transformity” concept (Bastianoni and Marchettini, 2000);
3. the calculation of each subsystem separately;
4. the Eigenvector Method (Patterson, 1983; Collins and Odum, 2000; Odum and Collins, 2003).

METHODOLOGY

Transformity values for the integrated production system were first calculated using the conventional method according to Odum (1996). The emergy theory establishes that in order to calculate the emergy content of two outputs, the emergy content of all the independent inputs must be summed, as the co-products carry the same emergy flow, according to the emergy algebra (Odum, 1996). The transformity is then calculated by dividing the total emergy content by the energy of each product.

The second approach we used is the “joint transformity” concept of Bastianoni and Marchettini (2000). These authors studied the problem of co-production in systems with more than one output by introducing the new concept termed "joint transformity", which is defined as the solar emergy required in order to obtain the products *x* and *y* divided by the sum of the energy content of the products *Ex* and *Ey.* According to these authors, the calculation of the transformities by summing the energy contents of all outputs allows a better comparison between systems with co-productions and systems with independent productions with the same outputs.

The third approach was made by splitting the farm system into three subsystems, grain, pig and fish production, and evaluating each subsystem separately.

Finally, we calculated the transformity values for the integrated production system using the Eigenvector method. The Eigenvector method (Patterson, 1983; Collins and Odum, 2000; Odum and Collins, 2003) uses energy systems diagrams to identify the flow of the available energy through the transformation processes within the energy network. For each transformation process, an equation equaling input emergy to output emergy is drawn. The data are combined in a matrix and the transformities are computed by minimizing the eigenvalues. The energy flows of the system can be represented in tabular ways, amenable to be solved using matrix mathematics. Table 1 shows the algorithm written using the commercial software MATHEMATICA, used to calculate a vector of transformity values by solving the emergy equations (Collins and Odum, 2000).

Table 1. Template drawn with the commercial program MATHEMATICA and used for the matrix calculations (Collins and Odum, 2000; Odum and Collins, 2003).

```
m={}
MatrixForm[m]
a=transpose[m].m;
p=Eigenvectors[a];err=m.Transpose[p];
MatrixForm[err];
MatrixForm[Transpose[p]];
Eigenvalues[a];
u=Min[Abs[Take[Eigenvectors[a],-1]]];
t=(1/u) Take[Eigenvectors[a],-1];
Matrixform[Transpose[t]]
```

RESULTS AND DISCUSSION

In this paper, four different methods were used to evaluate the transformity values for the integrated production system of grain, pig and fish: the conventional emergy methodology (Odum, 1996); the "joint transformity" concept (Bastianoni and Marchettini, 2000); the calculation of each subsystem considered separately, and the Eigenvector Method (Patterson, 1983; Collins and Odum, 2000; Odum and Collins, 2003).

According to the literature, transformity values for grain production are between 1x10^{5} and 4x10^{5} sej J^{-1} (Ortega et al., 2005; Brandt- Williams, 2002; Odum and Odum, 2001; Odum, 1996), whereas for animal production systems values are normally between 1x10^{6} sej J^{-1} and 3x10^{6} sej J^{-1}.

Transformities Calculated using the Conventional Method

The aggregated emergy diagram of the integrated production system, reported in Figure 2, shows the values of the emergy flows used to calculate the transformites for grain, pig and fish production according to Odum (1996). The values of the emergy flows were previously calculated by Cavalett et al. (2005).

The transformity value is calculated by dividing Y (the total emergy) by E_i (the energy content of the product expressed as food calories). For instance, the transformity of wheat is obtained by dividing the total emergy (3.25x10^{16} seJ) by the energy content of the wheat yield (1.96x10^{9} J). The calculated transformity for wheat was 1.65x10^{7} sej J^{-1}. Using the same procedure we obtained the following transformity values: soybean = 2.09x10^{6} sej J^{-1}; pig = 2.18x10^{6} sej J^{-1} and fish = 1.66x10^{7} sej J^{-1}.

With the exception of pig production system, the transformities calculated for wheat, soybean and fish were too high and are not in accordance with those found in literature. The calculated transformity is in accordance with the literature if only the system's main product is considered within the evaluation, although this procedure seems to lack accuracy.

Transformities Calculated using the "Joint Transformity" Concept

In Figure 3, the aggregated emergy diagram of the integrated production system is reported. According to the "joint transformity" concept, the output energy was obtained by adding up the energy of all products of the system.

The transformity value obtained for the integrated production system resulted in 9.48x10^{5} sej J^{-1}. This result seems to be a mean value of all the products. It can become useful to be compared with independent productions with same outputs. However, it is important to underline that this method is not able to differentiate the transformity of each product.

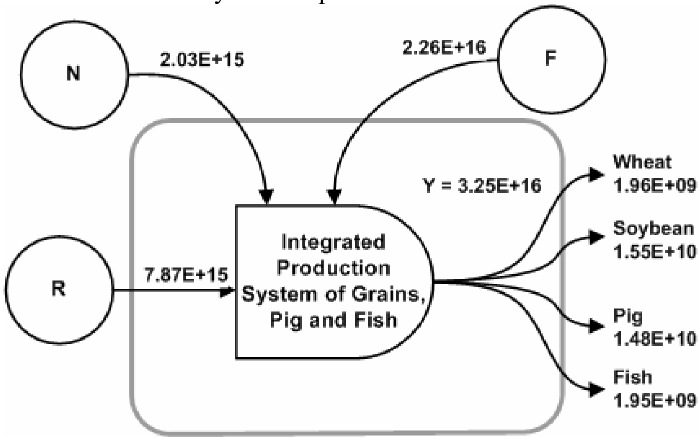

Figure 2. *Aggregated emergy diagram of the integrated production system showing the emergy flows used to calculate the transformity values according to Odum (1996). The emergy inputs are in seJ ha^{-1} year^{-1} and the outputs are in J ha^{-1} year^{-1}.*

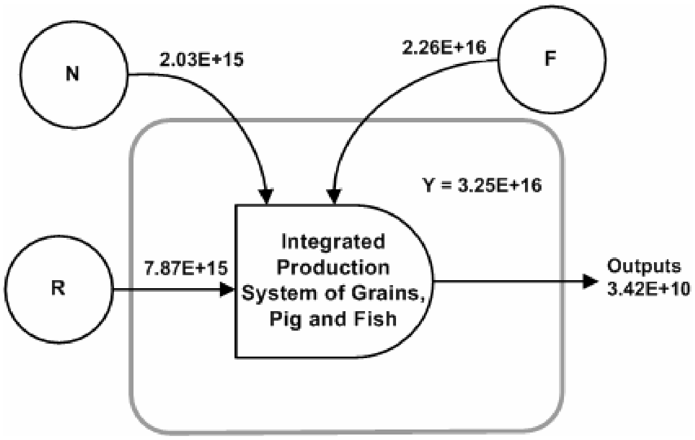

Figure 3. *Aggregated emergy diagram of the integrated production system showing the emergy flows used to calculate the transformity values according to the "joint transformity" concept. The emergy inputs are in seJ ha^{-1} year^{-1} and the outputs are in J ha^{-1} year^{-1}.*

Transformities Calculated for Each Subsystem Considered Separately

Accounting for the internal emergy flows (not only the external inputs) of the integrated production system allows the evaluation of each subsystem separately. Therefore, three different subsystems were considered: the first one dealing with grain production, the second with pig production, and the third with fish-farming (Figures 4, 5 and 6). In these figures the emergy inputs are expressed in seJ ha^{-1} year^{-1}, while the outputs are in J ha^{-1} year^{-1}.

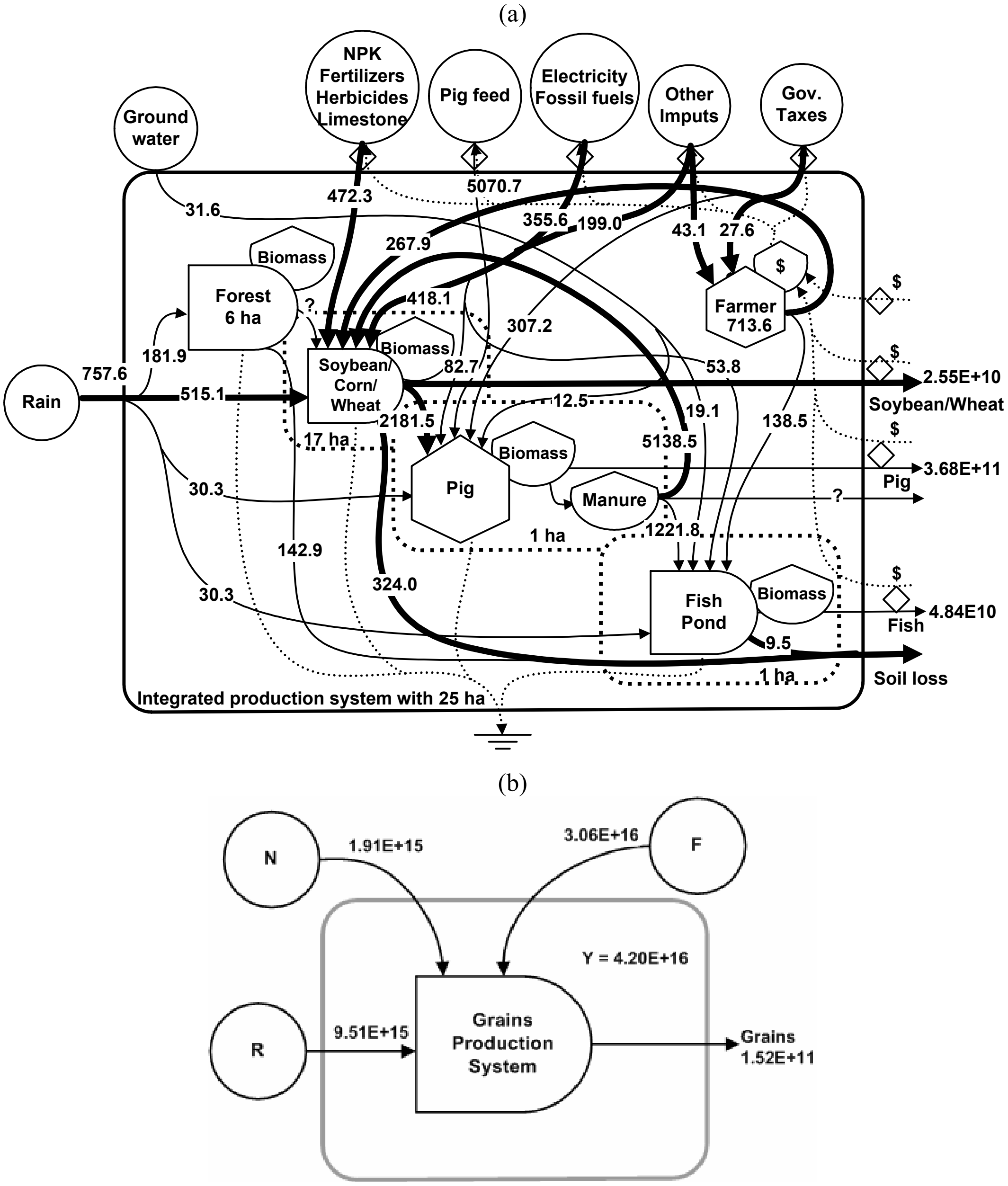

Figure 4. *(a) Emergy systems diagram of the integrated production system. The bold lines represent the emergy inputs (10^{14} seJ year^{-1}) and output (J year^{-1}) of the grain production subsystem. (b) Aggregated emergy diagram for the grain production subsystem. Emergy inputs in seJ year^{-1} and output in J year^{-1}.*

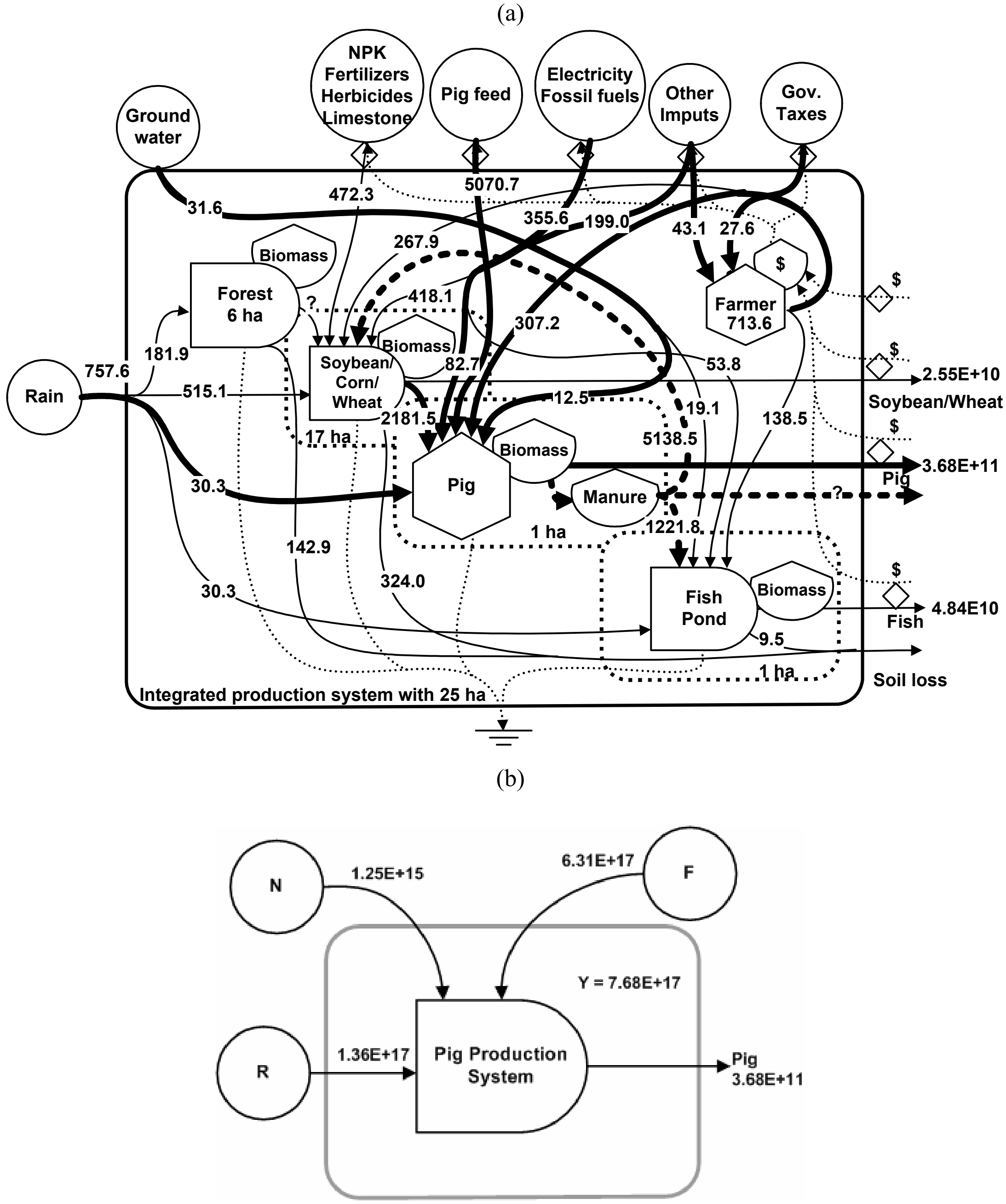

Figure 5. *(a) Emergy systems diagram of the integrated production system. The bold lines represent the emergy inputs (10^{14} seJ year^{-1}) and output (J year^{-1}) of the pig production subsystem. (b) Aggregated emergy diagram for the pig production subsystem. Emergy inputs in seJ year^{-1} and output in J year^{-1}.*

The transformity for each subsystem was calculated by using the conventional method according to Odum (1996). These values were previously calculated and published by Cavalett et al.

(2005). Using this method we obtained the following transformities: grains = 2.77×10^5 sej J^{-1}; pig = 2.09×10^6 sej J^{-1} and fish = 3.04×10^6 sej J^{-1}. Transformity values calculated for each subsystem considered separately are in agreement with the values found in literature. We consider this last method as the most appropriate to calculate the transformities for the case study reported here.

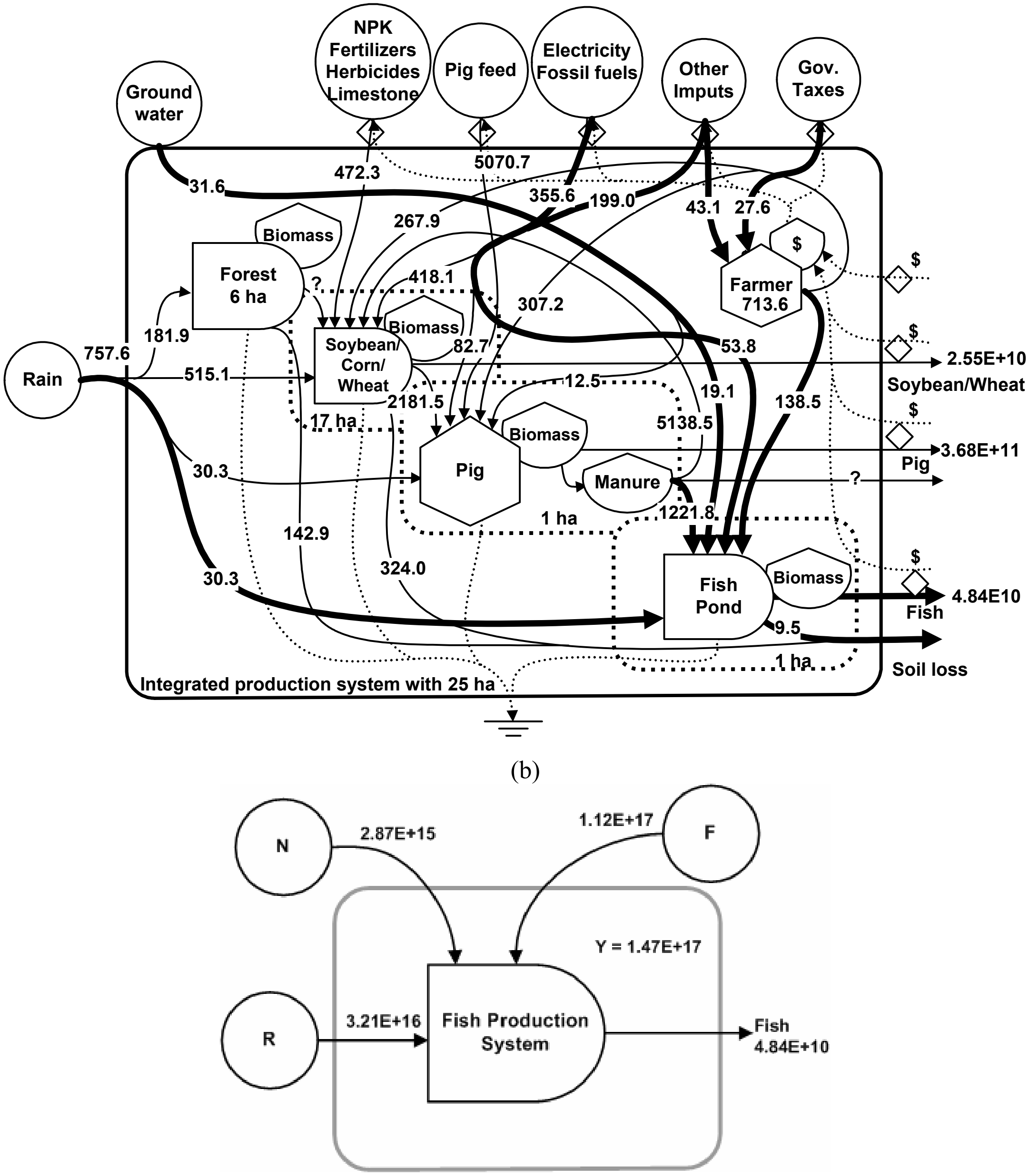

Figure 6. *(a) Emergy systems diagram of the integrated production system. The bold lines represent the emergy inputs (10^{14} seJ year^{-1}) and output (J year^{-1}) of the fish production subsystem. (b) Aggregated emergy diagram for the fish production subsystem. Emergy inputs in seJ year^{-1} and output in J year^{-1}.*

Transformities Calculated using the Minimum Eigenvector Method

Systems diagrams are made quantitative by estimating the values of energy flows for each transformation process. The numerical values are reported on the energy pathways of the system diagram. Closed loops are eliminated, since their net effect on steady state emergy is zero (Odum, 1996).

The matrix representing the integrated production system was solved considering one external energy source, as shown by the energy diagram in Figure 7.

The Matrix implemented to model the diagram of the integrated production system of figure 7 is:

$$\begin{vmatrix} 9.1\text{x}10^{16} & -4.3\text{x}10^{11} & 0 & 1.4\text{x}10^{12} & 0 & 0 \\ 5.0\text{x}10^{17} & 0 & -3.7\text{x}10^{11} & 0 & 0 & 0 \\ 5.0\text{x}10^{17} & 0 & 0 & -1.4\text{x}10^{12} & 0 & 0 \\ 5.0\text{x}10^{17} & 0 & 0 & 0 & -6.9\text{x}10^{11} & 0 \\ 2.3\text{x}10^{16} & 0 & 0 & 0 & 6.9\text{x}10^{11} & -4\text{x}10^{10} \end{vmatrix}$$

The output of the template drawn using the software MATHEMATICA, evaluating the transformities of the integrated production system considering three external energy sources is:

$$\left| \begin{array}{ll} \text{X1=} & 1 \\ \text{Grains =} & 1.36\text{x}10^{6} \\ \text{Pig =} & 1.35\text{x}10^{6} \\ \text{X4=} & 351617 \\ \text{X5=} & 721501 \\ \text{Fish =} & 1.30\text{x}10^{7} \end{array} \right|$$

The applications of this method found in literature deal with natural systems, where the sun is the main external energy source. For the integrated production system investigated in this paper, the main external energy source comes from economy. As the method calculates transformity values in relation to the main energy source, the calculated transformity values are higher than expected.

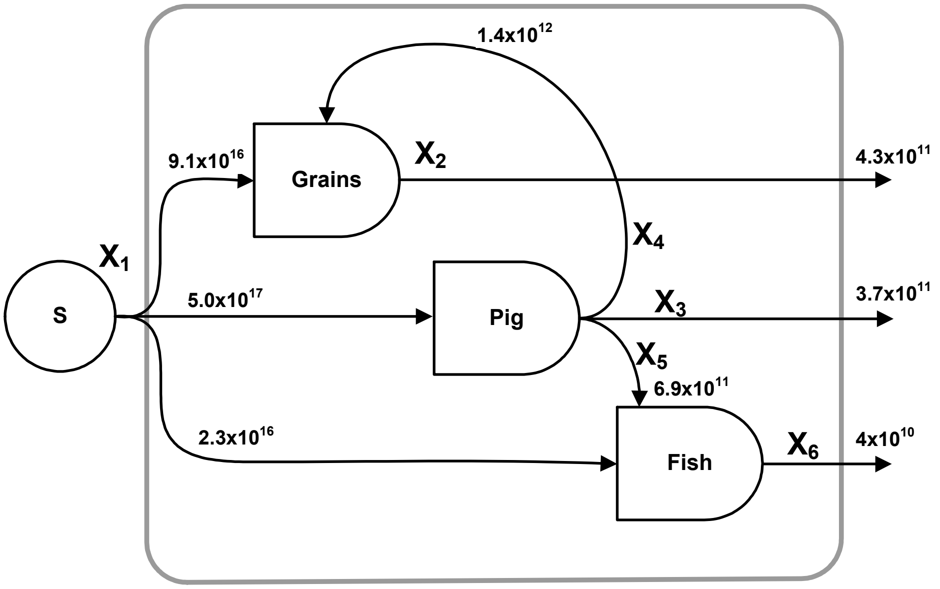

Figure 7. Energy systems diagram of the integrated production system with one external energy source. The values of the emergy source X_1 are in seJ year^{-1} and all the others energy flows are in J year^{-1}.

In order to avoid such a bias, we considered the environmental window encompassing the whole biosphere. The system uses only solar energy as external energy source, whereas the economy inputs used by the integrated production system studied here come from internal transformations of the solar energy and its energy flows values were estimated as a first approach. Figure 8 shows the diagram of the integrated production system put in the framework of a broader environmental window.

The Matrix implemented to model the diagram of the integrated production system of the figure 8 system is:

$$\begin{vmatrix}
5\text{x}10^{16} & -1\text{x}10^{14} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1\text{x}10^{14} & -1\text{x}10^{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1\text{x}10^{13} & -5.4\text{x}10^{11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1\text{x}10^{13} & 0 & -2.9\text{x}10^{12} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1\text{x}10^{13} & 0 & 0 & -3\text{x}10^{10} & 0 & 0 & 0 & 0 & 0 \\
8.4\text{x}10^{16} & 0 & 0 & 5.4\text{x}10^{11} & 0 & 0 & -4.3\text{x}10^{11} & 0 & 1.4\text{x}10^{12} & 0 & 0 \\
4.3\text{x}10^{15} & 0 & 0 & 0 & 2.9\text{x}10^{12} & 0 & 0 & -3.7\text{x}10^{11} & 0 & 0 & 0 \\
4.3\text{x}10^{15} & 0 & 0 & 0 & 2.9\text{x}10^{12} & 0 & 0 & 0 & -1.4\text{x}10^{12} & 0 & 0 \\
4.3\text{x}10^{15} & 0 & 0 & 0 & 2.9\text{x}10^{12} & 0 & 0 & 0 & 0 & -6.9\text{x}10^{11} & 0 \\
5.9\text{x}10^{15} & 0 & 0 & 0 & 0 & 3\text{x}10^{10} & 0 & 0 & 0 & 6.9\text{x}10^{11} & -4\text{x}10^{10}
\end{vmatrix}$$

The vector of transformities calculated by using the template drawn in MATHEMATICA is:

X1=	1
X2=	500
X3=	5000
X4=	92593
X5=	17065
X6=	$1.66\text{x}10^6$
Grains =	437628
Pig =	146703
X9=	38225
X10=	78667
Fish =	$2.75\text{x}10^6$

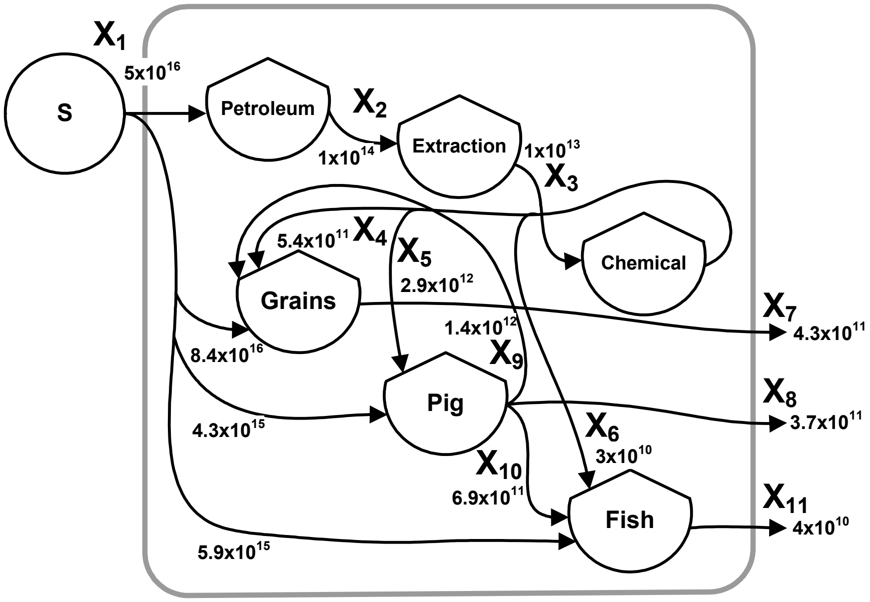

Figure 8. *Energy systems diagram of the integrated production system evaluated by using the broader window analysis. The values of the emergy source X_1 are in seJ year^{-1} and all the others energy flows are in J year^{-1}.*

This approach provided a more accurate emergy evaluation, as the results obtained for grain and fish subsystems are in agreement to the data found in literature and those calculated for each subsystem considered separately in this paper.

The value obtained for the pig subsystem seems lower than expected. However, it is also in agreement with results calculated for the pig subsystem considered separately since the manure is considered as another product in the accounting for pig production subsystem. If we consider not only the pig meat energy but also the pig manure energy as output in the calculation of the pig production the subsystem transformity, the value obtained is 1.61×10^5 seJ J^{-1}. The Eighenvalue method considers in the calculation the whole web of energy flows in the system and, because of that, also considers manure an output of the pig subsystem. Therefore the value of the pig subsystem transformity calculated by the Eighenvalue method (1.46×10^5 seJ J^{-1}) is in agreement with the value obtained for pig production subsystem considering the energy of manure in the transformity calculation (1.61×10^5 seJ J^{-1}).

Also, it is important to notice that the system does not export manure. It uses all manure produced to fertilize the crops and the fish ponds. In this paper we assume that the data collected from farm systems are correct.

Summary of the Results Obtained in the Different Methods used to Calculate Transformities

In this paper we have presented four approaches for the calculation of the integrated system transformity. Table 2 shows the summary of the results obtained.

Table 2. Transformity values calculated by using the four different method: a comparison.

Method	Transformity (sej J^{-1})		
	Grains	Pig	Fish
Conventional emergy methodology	Soybean:2.09×10^6 Wheat: 1.65×10^7	2.18×10^6	1.66×10^7
"Joint transformity" concept	Outputs: 9.48×10^5		
Each subsystem considered separately [1]	2.77×10^5	2.09×10^6	3.04×10^6
Each subsystem considered separately [2]	2.77×10^5	1.61×10^5	3.04×10^6
Eigenvector method	4.37×10^5	1.46×10^5	2.75×10^6

[1] Considering only main product of each subsystem

[2] Considering all the products of each subsystem

CONCLUSIONS

The results obtained from the four different approaches allow pointing out that:

- Most of the values obtained using the conventional emergy methodology are not in accordance with the literature.
- The transformity value calculated using the joint transformity concept is in accordance with the literature. However, this method is not able to differentiate the transformity of each product.
- The transformity values calculated considering each subsystem separately are in accordance with the literature. This procedure seems to be the most suitable to calculate the transformities of the integrated production system. However, this approach requires a deep knowledge about the internal emergy flows of the system under investigation.
- The Eigenvector method allows to differentiate the subsystems, providing transformity values for each product. We obtained more reliable results using this method with a broader window

approach. Even though this method is hard to implement, due to the difficulties implied in the evaluation and calculation of the internal emergy flows, we think that it could provide a deeper understanding of natural and human-dominated ecosystems.

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