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Integrating or Des-integrating agribusiness systems: Outcomes of emergy evaluation

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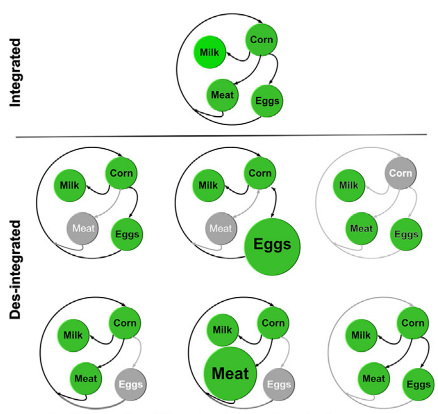
HIGHLIGHTS

- The benefits of integration in a crop-livestock system was evaluated through emergy synthesis.
- Efficiency evaluation of the (des)-integration of corn, eggs, pork and milk production was calculated.
- Seven scenarios studied: the integrated existing system and scenarios in which one of the productive subsystems is removed.
- The trade-offs between the sustainability and productivity were highlighted and discussed.
- The increase of systems/processes to be integrated does not guarantee the best environmental performance.

GRAPHICAL ABSTRACT

(Des) Integrating different agricultural production systems



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ABSTRACT

The agribusiness contributes significantly to the Brazilian domestic production, and the search for environmentally friendly systems, exploring the maximum possible use of renewable resources and reducing the use of non-renewable ones, affects the agribusiness' productivity and competitivity. An agribusiness producing corn, eggs, pork and milk was evaluated using emergy accounting. The effects of the (des)integration of the production processes on the efficiency and environmental sustainability of the system were assessed using seven scenarios. The first is the existing integrated system and the others are scenarios in which one of the productive subsystems is removed. Efficiency is measured by the global productivity relative to the amount of protein produced. The most environmentally advantageous scenario, in terms of sustainability and productivity, is the one in which pork production is increased and egg production is ceased. This result suggests that increasing integration per se cannot assure gains in environmental sustainability. The integrated management of the residues of the poultry and pig production as organic fertilizer resulted an advantage for the seven scenarios. The scenarios presented should help to evaluate organizational innovations and to identify trade-offs that could influence the environmental performance of agricultural integrated systems.

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1. Introduction

Agriculture is a key driving force responsible for the surpassing of some world limits as it leads to biodiversity loss and land degradation (Foley et al., 2011). Additionally, present agriculture is acknowledged as the most significant cause of ecosystem services loss (Fagerholm et al., 2016). In general, intensive agriculture is dedicated on improving productivity, demanding an enormous quantity of non-renewable supplies, such as fertilizers and pesticides, fuels, and equipment. Therefore, concerns are directed to the design of agricultural production systems that consider the use of renewable resources and protect the environment (Foley et al., 2011). According to Paolotti et al. (2016) animals may occupy productive land, and combining livestock with plantations and orchards may result in lower land use and lower need for fertilization, weeding and pest control.

The Brazilian agricultural sector had an increase of 1.3% in 2019 representing 5% of the gross domestic product (Brazil, 2020). In this context, the environmental impacts caused by the increase in crop areas to meet the global demand, the need to increase productivity with the intensive use of fertilizers and machinery and the deforestation provoked by the sector growth must be observed with attention and concern. In parallel, the worldwide protein consumption demands animals that are bred and fed with the intensive use of area demanding cereals. Agribusiness managers are then increasingly concerned with environmental sustainability, seeking the best possible use of local renewable resources and reducing the use of non-renewable resources, without affecting the productivity and the competitiveness of the agribusinesses.

Concerns about the sustainability of agribusiness are now focused on the need to develop agricultural technologies and practices that: (i) do not have adverse effects on the environment (partly because the environment is an important agricultural asset); (ii) are accessible and effective for farmers and (iii) result in improvements in both food productivity and positive effects on environmental goods and services. The search for sustainability in agricultural systems incorporates concepts of resilience (the ability of systems to withstand disruption and stress) and persistence (the ability of systems to continue for long periods) and seeks broader results in the economic, social and environmental sectors.

Considering that agroecosystems or agribusinesses are altered ecosystems (Odum and Barrett, 2004; Swift et al., 2004; Peterson et al., 2017) with different variables (productivity, stability, trophic relationships, resilience, dependence on external resources, etc.), their sustainability has been associated with the replacement of some practices for others that imitate those of natural systems without significant damage to productivity and preserving the functions of the ecosystem of environment (Rydberg and Jansen, 2002; Firbank et al., 2006, 2008).

Among the technologies and practices proposed to improve productivity and the use of the natural capital of agroecosystems the integrated management appeared as a strong option. Studies on integrated management were carried out considering the life cycle assessment (Korres, 2013; Wangunci and Zhao, 2019), the system footprints (Jiang et al., 2020; Chi et al., 2020) and the systems environmental efficiency (Wilkins, 2008). Emergy evaluation stands as a robust tool (Giannetti et al., 2013), which is capable to show how environmental management can (or not) maximize financial performance, allowing to itensificate production systems and the livestock integration in production systems (Patrizi et al., 2018). The method comes up as a counterpart in evaluating the sustainability of production systems, as it includes the donor side viewpoint considering all energy/materials inputs required by the production system.

Among the studies using the emergy accounting to evaluate the sustainability of agribusiness, there are studies that prioritize increasing the efficiency of the use of resources (Lagerberg and Brown, 1999; Bastianoni et al., 2001; Giannetti et al., 2011a, 2011b) and those that compare different production models, such as organic and conventional (Ortega and Sarcinelli, 2004; Ortega et al., 2005; La Rosa et al., 2008). In both cases, the use of renewable resources resulted in low production costs and a consequent increase in competitiveness in agreement with the results of Shah et al. (2019) who assessed the nature's and human's contribution to agriculture through renewability and non-renewability.

The potential of integrative farming involving both crops and livestock was explored by several authors. Cavalett et al. (2006) evaluated an integrated system producing grain, pork and fish, and showed that the integrated systems had a higher emergy efficiency, higher capacity to use local resources and higher efficiency in energy conversion. The integration of geese and corn plantation led to economic benefits, higher sustainability and lower environmental pressure (Sha et al., 2015), as well as the integration of cropping, poultry and fish (Cheng et al., 2017), in spite of the use of nonrenewable resources for cropping production.

Rodríguez-Ortega et al. (2017) pointed to the need of additional support on the use of local and renewable natural resources to safeguard long-term sustainability of different sheep-crop farming systems according in Spain, and Xu et al. (2017) proposed an integrated rice-duck farming to mitigate global warming while improving rice yield. Finally, Patrizi et al. (2018) who assessed the sustainability of the integration of a goose raising system with an organic grape production, claimed that the integration of crop and livestock can be a solution for the increasing demand of food due to a growing world population.

The integration of crop and livestock, in general, is presented as a way to reduce the intensive use of machineries for weeding and of chemical fertilizers – and consequently, the use of non-renewable inputs – and to reduce the environmental load through the intensification of recycling and integration of subsystems. Despite the many studies that highlight the benefits of integrating animals with vegetable planting, there is still no studies evaluating how far such integration can go, or whether there is a threshold or optimal point in which integration may cause less damage to the environment.

This work evaluates an integrated agribusiness, located in the city of São Sebastião do Paraíso, Minas Gerais, Brazil. The agrosystem includes the production of corn, eggs, pigs and milk, and the study evaluates the environmental sustainability of the agribusiness from the perspective of the biosphere exploring the effects of the (des)integration of food production processes with respect to their sustainability and global efficiency.

2. Method

Among the several sustainability assessment tools, emergy evaluation is particularly suitable to analyze systems at the interface between biosphere and the economy because it converts all inputs of the production process to a common unit: equivalent solar energy, directly or indirectly, required to make a product or a service (Odum, 1996). Standardizing all inputs into a common unit is a clever solution to quantify processes and activities, and the quantity of energy used to obtain a product unit can be interpreted as an indicator of quality and efficiency (Giannetti et al., 2019). All the necessary inputs to obtain a product or service include the contributions of nature (solar irradiation, rain, wind, water, soil) and those provided by the economy (materials, fuels, machinery, labor). Thus, the emergy approach can deliver a structure for the evaluation of various energy flows interacting in agricultural production systems allowing the understanding of energy efficiency in the whole system (Rodríguez et al., 2019). In this work, the emergy accounting is carried out in three stages:

1st stage: construction of an energy diagram defining the system boundary and all sources of energy and materials that feed the system, the interactions of the process and its outputs. The time window evaluated is one year and all inputs required for the production processes involved are counted.

2nd stage: From the diagram, a table with all the energy and material inputs of the system, identified as Renewable, Non-Renewable or the Feedback from the economy, is constructed. Raw data (energy, mass, volume) were obtained in loco (See Supplementary Materials) and the unit emergy values (UEVs) were obtained from the available literature under the 12.0E + 24 seJ/yr baseline (Brown et al., 2016). The emergy is calculated by multiplying the raw quantities (energy, mass, volume) by the respective UEV.

3rd stage: calculation of emergy indices, global productivity and interpretation.

2.1. Emergy indices

The total emergy flow supporting the any system can be decomposed in renewable (R), non-renewable (N) and purchased resources (F - the feedback from the economy). The distribution of these flows determines the values of the emergy indices. Resources are considered renewable when they are consumed at a slower rate than nature is able to replenish; otherwise, the resource is considered non-renewable. The emergy indices allow relating the use of renewable and nonrenewable natural resources and the feedback from the economy.

- Emergy Yield Ratio: EYR = (R + N + F) / F. This indicator is used to assess the system's ability to exploit local natural resources (renewable and non-renewable) without differentiating them (Odum, 1996).
- Emergy Investment Ratio: EIR = F / R + N. This indicator evaluates the most economically competitive alternatives, confronting the use of resources from the economy and the biosphere (Odum, 1996).
- Environmental Load Ratio: ELR = (N + F) / R. It shows the load that the necessary flows for the implantation and operation of the farm impose to the environment. The ELR indicates the tension that the studied system generates in the ecosystem (Odum, 1996).
- Environmental Sustainability Index: ESI = EYR / ELR, with the concept of sustainability linked to maximization of yield and minimization environmental pressure (Brown and Ulgiati, 2002).
- Global productivity (GP): Traditional productivity is calculated as the ratio of outputs and inputs (inputs/outputs) while global productivity considers biosphere services as renewable resources and non-renewable resources. Therefore GP is more comprehensive than the normally calculated productivity. The global productivity is obtained by the relation between energy and the emergy, that is, the inverse of the transformity or the UEV (Almeida et al., 2010). In order to make a more useful analysis regarding sustainability, global productivity was calculated in grams of proteins/seJ for each scenario and the integrated system. The higher the value of this indicator, the better the use of energy and materials by the system under consideration.

2.2. System description

The Braghini Farm is located in the city of São Sebastião do Paraíso (Minas Gerais), and has an area of 101 ha, 55 ha used to plant corn, 36 ha destined to the pastures needed to raise cattle and in the other 10 ha are occupied by houses, sheds etc. The agribusiness produces and sells eggs and pork meat. The milk produced is donated to employees and charity institutions in the neighborhood. For its operation, the property has a headquarters house, six houses for employees, 18 sheds and three rainwater dams. The workforce required for the existing production systems is 30 employees, 14 of which carry out activities in more than one process or perform activities common to all processes, 10 are dedicated exclusively to the egg production and 6 are exclusive of the meat production process.

The agribusiness produces yearly approximately 90 tons of corn, and the plantation uses, intensively, seeds, fertilizers and fossil fuel. As a way to minimize the use of external resources, the property takes advantage of the pigs and poultry residue for soil fertilization. This corn is used in the animal feed composition (poultry, pigs and cattle) in an attempt to increase the use of local resources.

In the egg production system, the farm has 40,000 birds (22,000 producing and 18,000 growing) that produce 410,400 eggs per month and consume 56 tons of animal feed per month. The energy of the birds was not considered as one of the system's inputs, since the birds breed internally.

For the meat production, the farm has 3000 pigs that consume 120 tons of animal feed per month. The amount of meat produced monthly is approximately 26 tons. The energy of the pigs was not counted as input, since the pigs reproduce internally. The farm has also 120 cows, producing 18,000 L of milk and consuming 4 tons of animalfeed per month. Milk production is not destined to commercial use, and the scenario “no milk” was not considered in this study, but the cows consume animal feed (corn) and their presence interferes in the overall operation of the system. The cows manure is not used in the corn field.

2.3. Systems and scenarios analysis

According to the Report Our Common Future (Comissão Mundial sobre Meio Ambiente e Desenvolvimento, 1988), for sustainable development to be achieved there must be a balance among the environment, the economy and society. Therefore, the scenarios assessed were posed in a way that the producer would keep the same income and the reduction of the number of employees would be the lowest possible (Castellini et al., 2006; Martin et al., 2006; Hu et al., 2012).

The system has been decomposed to determine the system configuration that maximizes productivity but maintains or increases the system sustainability. To this end, two configurations were proposed:

- the total interruption of one of the products production and
- the interruption of the production of one product along with the increase of the production of another one to keep the incomes.

3. Results and discussion

The diagram in Fig. 1 represents the energy and material flows of the integrated agribusiness of Braghini Farm. In this system, the environmental cost of implementing and operating the integrated production process of the property is evaluated. The system boundary covers the maintenance (operation) of the system within one year time window (represented by the larger rectangle). Deployment, soil, water and pasture were represented by stock symbols. The input flows of energy and materials are represented in increasing order of quality (emergy per unit) from left to right, with flows of renewable natural resources (sun, rain and wind) in the left of the diagram, non-renewable natural resources (soil) and the feedback from the economy (electricity, seed, equipment, fuel, soybean meal, corn, fertilizer and labor). The animal feed is represented as stock for feeding poultry, pigs and cattle. 70% of corn used is produced in the farm and the remaining 30% come from an external source (economy). The rectangle in gray delimits the window of the studied system and the final co-products: eggs, meat and milk.

Table 1 shows the accounting in emergy of Fazenda Braghini, in which all the inputs required for the implantation and operation of this agribusiness were accounted for (the data collected and detailed calculations are shown Supplementary materials). The labor force is the most significant resource in the total emergy value of the farm

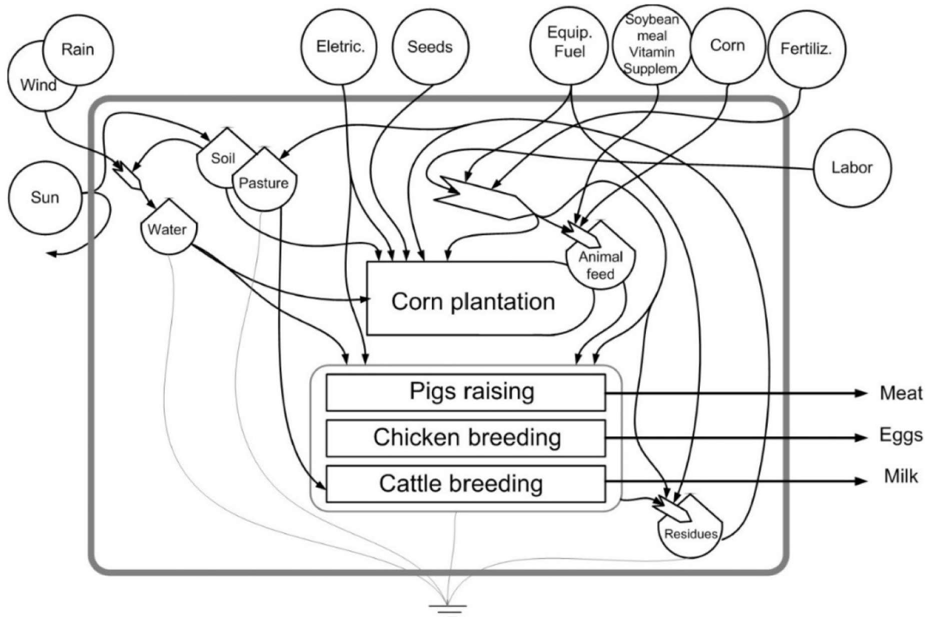

Fig. 1. Energy diagram of the operation of the integrated system of Fazenda Braghini.

Table 1
Emergy accounting of the integrated productive system of Fazenda Braghini.

Item	Description	Unit	Quant. (unit/year)	UEV (seJ/unit)	Emergy 10^{14} (seJ/year)	% (seJ/seJ)	Refs.[b]
Infrastructure							
1	Concrete	g	3.16E+08	1.17E+09	3687	15	(a)
2	Steel	g	1.05E+07	3.14E+09	330	1	(a)
Operation							
3	Sun	J	1.41E+13	7.58E−01	0.1	<1	By definition
4	Rain (chemical)	J	9.03E+12	3.89E+04	3516	14	(b)
5	Rain (geopotential)	J	4.48E+10	2.24E+04	10	<1	(b)
6	Wind	J	2.11E+11	3.12E+03	7	<1	(b)
7	Fertilizers	g	4.90E+07	6.58E+09	3226	13	(b)
8	Soil loss (plantation)	J	3.11E+11	9.39E+04	292	1	(b)
9	Soil loss (pastures)	J	7.32E+09	9.39E+04	7	<1	(b)
10	Electricity	J	6.91E+11	4.27E+05	2952	12	(b)
11	Fuels	J	1.57E+10	1.41E+05	22	<1	(b)
12	Labor	J	9.80E+10	8.71E+06	8538	34	(c)
13	Water	m^3	2.19E+04	7.95E+11	174	1	(d)
Corn production[a]							
14	Seeds	g	1.08E+06	4.96E+08	5	<1	(e)
Feed for egg production							
15	Corn production	g	1.18E+07	1.58E+09	186	1	(f)
16	Soybean	g	1.12E+07	2.47E+09	277	1	(f)
17	Feed core	g	5.60E+06	4.61E+09	258	1	(g)
Feed for pigs production							
18	Corn	g	2.52E+07	1.58E+09	397	2	(f)
19	Soybean	g	2.40E+07	2.47E+09	593	2	(f)
20	Feed core	g	1.20E+07	4.61E+09	553	2	(g)
Feed for milk production							
21	Corn	g	8.40E+05	1.58E+09	13	<1	(f)
22	Soybean	g	8.00E+05	2.47E+09	20	<1	(f)
23	Feed core	g	4.00E+05	4.61E+09	18	<1	(g)
	Total emergy				25,064	100	
Outputs							
24	Eggs	g	2.71E+08	9.25E+09			
25	Meat (pork)	J	3.09E+12	8.11E+05			
26	Milk	g	2.23E+08	1.12E+10			

The values of the UEVs refer to the 12.0E + 24 seJ/yr baseline (Brown et al., 2016), and solar radiation and wind were not considered to avoid double counting (Odum, 1996).
[a] Only 30% of corn used come from an external source, the 70% produced in the property were not accounted.
[b] (a) Brown and Buranakarn, 2003, (b) Odum, 1996; (c) Bonilla et al., 2010; (d) Buenfil, 2001; Panzieri, 1995; (f) Ortega et al., 2002; g) Cavalett et al., 2006.

(34%), due to the number of employees distributed in the four processes of food production (corn, eggs, pork and milk). Concrete (15%), rainfall (14%), fertilizers (13%) and electricity (12%) also contributed significantly to the total emergy of the system.

The total emergy flow of the integrated system (2.51E+18 seJ/year) indicates how much material and energy is annually invested in the integrated agribusiness.

3.1. Potential scenarios to evaluate the effectiveness of the integrated system

Six scenarios are studied in which one of the productive subsystems is removed (Table 2). Efficiency is measured by the global productivity and scenarios mimic situations in which the production of one product is completely ceased along with (or without) the increase of the production of another one to keep the incomes. In order to verify if integrated management, which seeks to reduce the need to import inorganic fertilizers (Goulding et al., 2008), is an important factor in the search for sustainable development, the following scenarios have been also established:

- interruption of the production of corn in the property;
- discontinuation of the use of livestock waste in corn production.

Table 3 summarizes the results of the integrated productive system of Fazenda Braghini in comparison with those obtained from the six scenarios proposed.

3.1.1. System without meat production with and without increasing eggs production

By removing pigs raising, the farm would no longer buy corn from external sources and part of the corn produced should be sold, being the excedent corn, eggs and milk the outputs of the system. Under this scenario, the system operates with 24 employees (10 exclusive of egg production and 14 who work in all production systems). The use of electricity reduces 70% in relation to the actual system (50% is used in the egg production and 20% in all other processes) and water use is reduced to 60% (40% used in egg production and 20% in all other processes).

The emergy evaluation of the scenario without meat production (Table 3) shows the labor force as the most significant resource in the total emergy value (38.8%). The other significant contributions are rain (18.2%), fertilizers (16.7%), electricity (10.7%) and concrete (9.4%).

When the production of meat is ceased, an increase of 2.13 times in eggs production to replace is required to maintain producer revenues. In this scenario, part of the corn produced on the property can also be sold. The outputs of the process are then corn, egg and milk (Table 3). The labor force has the largest contribution to the total emergy value (37.2%). Fertilizers (18.4%), electricity (12.8%), concrete (12.6%) and rain (12%) also have a significant participation in the system's total emergy.

3.1.2. System without eggs production with and without increasing meat production

To evaluate the opposite scenario presented in the previous section, the following situations were simulated: (i) the total interruption of egg production and (ii) the total interruption of egg production with a 1.89-fold increase in pig production to keep the producer revenues. By removing poultry (egg production) from the process, part of the corn produced on the property becomes a product, and in this case the farm does not need to buy corn from external sources. The outputs of the process are corn, meat and milk.

In this scenario, inputs from implantation materials that are unique to egg production have been excluded (employees' homes and sheds). The number of employees is reduced to 20 (6 exclusive of meat production and 14 that perform tasks shared by all productive systems). In addition, the percentages referring to the consumption of electricity and water were also adjusted to 50% of the total emergy of the integrated system (30% used in meat production and 20% of all processes) and a reduction of 40% in water use (40% of production of meat and 20% of all processes). As shown in Table 3, the most significant resource in the total emergy value is labor (33.8%). The other inputs that also contribute

Table 2
Description of the scenarios considered to value the performance of the agro-livestock system.

Scenarios[a]	Products	Characteristics/consequences of the (des)integration	Financial income
Integrated	Eggs Meat Milk	Actual system	No change
No meat	Eggs Milk Corn	Reduced infrastructure Reduced electricity consumption Reduced man labor Reduced water consumption No need of buying extra corn	Reduced income
No meat/increase eggs production in 2.13 times	Eggs Milk Corn	Reduced electricity consumption Reduced man labor Reduced water consumption No need of buying extra corn	No change
No eggs	Meat Milk Corn	Reduced infrastructure Reduced electricity consumption Reduced man labor Reduced water consumption No need of buying extra corn	Reduced income
No eggs/increase meat production in 1.89 times	Meat Milk Corn	Reduced infrastructure Reduced electricity consumption Reduced man labor Reduced water consumption	No change
No corn	Eggs Meat Milk	Reduced man labor No soil loss in crop plantation No fertilizers required	No change
No animal residues recycling	Eggs Meat Milk	Increased of chemical fertilizers consumption	No change

[a] The withdrawal or alteration of milk production was not considered, since this process requires a very small use of resources in its implementation and operation, in addition to its small revenue in relation to the other processes.

Table 3
Emergy accounting of seven potential scenarios of Fazenda Braghini.

Item	Description	Emergy/10^{14} (seJ/year)					No corn production	No animal residues recycling
		Integrated system	No meat production	No meat/increasing eggs production	No eggs production	No eggs/increasing meat production		
Infrastructure								
1	Concrete	3687	1811	3682	2159	3682	3689	3682
2	Steel	330	186	330	213	330	292	330
Operation								
3	Sun	0.1	0.1	0.1	0.1	0.1	0.1	0.1
4	Rain (chemical)	3516	3515	3515	3515	3515	3515	3515
5	Rain (geopotential)	10	10	10	10	10	10	10
6	Wind	7	7	7	7	7	7	7
7	Fertilizers	3226	3227	3227	3227	3220	17	5379
8	Soil loss (plantation)	292	292	292	292	292	0	292
9	Soil loss (pastures)	7	7	7	7	7	17	7
10	Electricity	2952	2068	3735	1477	2265	2955	2947
11	Fuels	22	22	22	22	22	7	22
12	Labor	8538	7485	10,909	6235	8106	8106	8561
13	Water	174	105	183	105	166	174	174
Corn production								
14	Seeds	5	5	5	5	5	0	5
Feed for egg production								
15	Corn	186					617	186
16	Soybean meal	277	277	589			277	277
17	Vitamin supplements	258	258	549			258	258
Feed for pigs production								
18	Corn	397				1136	1326	397
19	Soybean meal	593			592	1121	592	592
20	Vitamin supplements	553			553	1045	553	553
Feed for milk production								
21	Corn	13				20	44	13
22	Soybean meal	20	20	20	20	20	20	20
23	Vitamin supplements	18	18	18	18	18	18	18
	Total emergy	25,064	19,296	27,084	18,441	24,971	22,477	27,227

significantly to the total emergy are rain (19%), fertilizers (17.5%), concrete (11.7%) and electricity (8%).

A consequence of increasing 1.89 times the production of meat to keep the producers revenues unchanged without producing eggs is that the corn produced by the farm is not enough and there must be an increase of corn bought from external sources (Table 3). The system's outputs in this scenario are meat and milk, and labor accounts for 31.5% of the total emergy. The second largest contribution to the total emergy is concrete (14.4%). Rain, fertilizers and electricity contributed, respectively, with 13.7%, 12.6% and 11.5%.

3.1.3. System without corn production

By simulating the process without the production of corn, all corn for the production of the animal feed must come from the economy. Eggs, meat and milk are the outputs of this system. The soil loss was recalculated, since the 55 ha of the plantation were added to the 36 ha of pasture. Fuel consumption could be reduced to 30% and only 26 employees were required. The emergy results simulated without corn production is presented in Table 3, in which the labor force contributes most significantly to the total emergy of the system (36.1%). Concrete (16.4%), rain (15.7%) and electricity (13.1%) also contribute significantly to the total emergy flow required by this scenario.

3.1.4. System without recycling animal wastes

When the production of Fazenda Braghini is simulated without the use of the animal residues there is an increase in the amount of fertilizers used to supply nutrients to the soil that were previously partially replaced by the organic fertilizer. The outputs of the process are: eggs, meat, milk and animal waste. Table 3 shows the emergy evaluation of the agribusiness operating without the use of the animal residues, and labor is the most significant resource in the total emergy of the farm (31.4%). Fertilizers (19.8%), concrete (13.5%), rainfall (12.9%) and electricity (10.8%) also have a great contribution to the total emergy of the system.

3.2. Overall results

Fig. 2 summarizes the composition of the emergy flows required by each system aggregated into major categories, highlighting the differences between the seven production processes studied and the contribution of each category to total emergy. It is observed that labor is the input that contributes most in all systems and that the share of soil loss is negligible. By evaluating the options in which the producer can maintain his income equal to that obtained by the integrated system, the system with the lowest relative contribution of renewable energies is egg production (no meat increasing eggs), which requires more labor and energy (fuels and electricity). The income for the option “no animal waste recycling” will depend on the costs and fate (economic and environmental) of the animal waste disposal.

Table 4 summarizes the results obtained with respect to the global production efficiency of each scenario, including the integrated system and results in the literature. The results are shown in relation to the functional grams units of protein, which allows unifying the output of all systems and compare the total protein production of each of them.

Table 5 shows that the integrated production is less efficient than the isolated production of meat (no eggs and 1.89 times the meat production to maintain income) and that the domestic production of corn decreases the integrated system global productivity in about 13%. If the

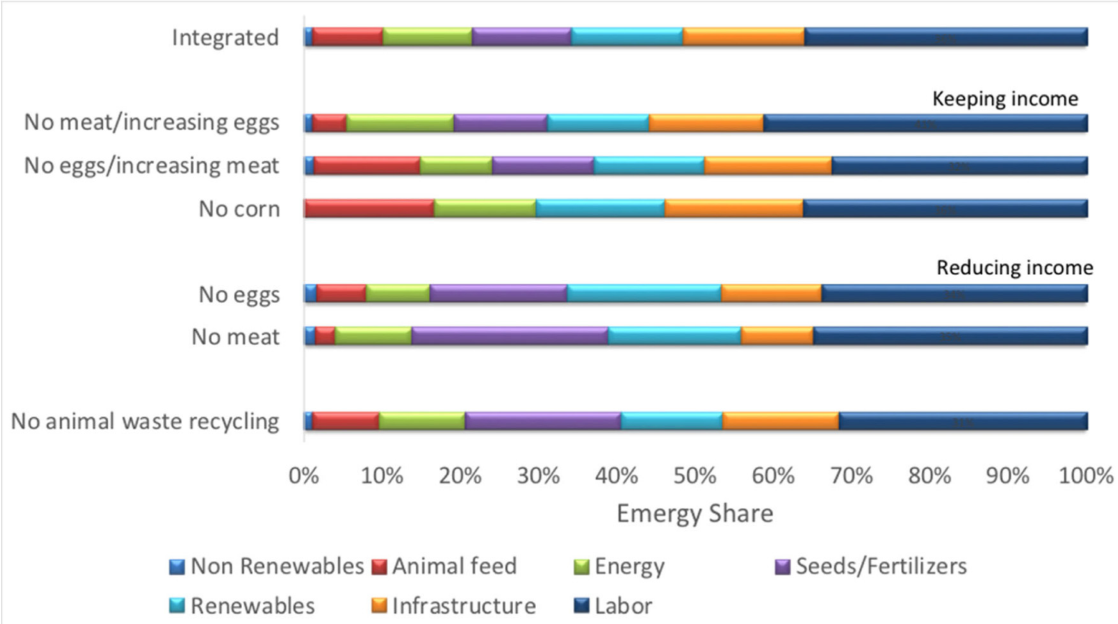

Fig. 2. Emergy inflows required by each system aggregated into major categories: Soil loss; Animal feed (corn, soybean meal and vitamin supplements); Energy (fuel and electricity); Seeds and Fertilizers; Renewables (chemical rain); Infrastructure (concrete and steel); and Labor.

animal wastes are not recycled, the reduction in the global productivity of all scenarios is approximately 5%. In the case of eggs production with maintenance of the financial income, it is noticed that there is an increase in efficiency when compared to the integrated production. It is interesting to note that the interruption of corn production increases the production efficiency of the three products in relation to the integrated system. According to several authors (Altieri, 1995; Wilkins, 2008; Patrizi et al., 2018), livestock integration can improve the environmental performance of agricultural systems, however, the comparison among the scenarios shown in Table 4 indicates that the integration per se is not warranty of improvement, and that some combinations may decrease the global productivity. In Table 5, the emergy indices obtained for the seven configurations studied are compared.

It can be seen in Table 5 that there is no significant variation of EYR (1.2 ± 0.1) among the scenarios studied, suggesting that the appropriation of natural resources by any of them contributes similarly to the overall environment. When it comes to the environmental load (ELR), the interruption of egg production would reduce the ELR value of the integrated system by approximately 4% if the current revenue is maintained. Therefore, in spite of the greater efficiency in the transformation of resources, the increased egg production does reduce the environmental load of the system significantly. In the scenario with the interruption of the meat production maintaining the revenues, a 7% increase in the ELR value is observed. The scenario in which corn production was withdrawn shows a 15% reduction in the ELR value, resulting in a 20% increase in the value of the sustainability index (ESI), while in the scenario in which the use of animal residues was interrupted, there is a 20% increase in ELR with a 10% reduction in ESI. In general, a decrease in the environmental load can only be observed if the system size is decreased, and all scenarios show similar environmental performance in regard to the environmental yield ratio and the environmental sustainability index.

Table 4
Comparison of global productivity (grams of protein obtained/seJ invested) obtained in this study compared with those reported in the literature.

Scenario	Global productivity/10^{11} (g/seJ)				
	Eggs	Meat	Milk	Corn	Total
Integrated	1.36	3.05	0.29	0.001	4.73
No meat	1.82		0.39	0.08	2.29
No meat/Increasing eggs	2.74		0.28	0.002	3.02
No eggs		4.26	0.41	0.002	4.68
No eggs/increasing meat		5.97	0.30		6.29
No corn	1.56	3.50	0.34		5.43
No animal waste recycling	1.29	2.89	0.28		4.49
Literature[a]	0.16 a 0.02 b	1.61	0.13	2.04	

[a] Brandt-Williams (2002) (eggs), Cavalett et al. (2006) (beef), Brandt-Williams (2002) (milk) and Ortega et al. (2002) (corn).

Separating the outputs of each scenario and confronting the ESI of each scenario with their global productivity shows that, as expected, the worst scenario is that in which the animal waste is not used (Fig. 3). However, the corn production shows the lowest global productivity among all farm's products. The "no corn" scenario shows higher ESI values and higher GP values than those of the integrated system (when each outcome is considered separately and also when the system is considered as a whole, Table 5). This result indicates that there is a hierarchy that should be considered when designing an integrated system. If the producer already has a corn plantation, the inclusion of protein production (eggs or meat) will aggregate value to his product (both in quality and in economic terms). The global productivity of the business will increase as well as its sustainability.

Despite the many studies that highlight the benefits of integrating animals with vegetable planting, there is still no studies evaluating how far such integration can go, or whether there is a threshold or optimal point in which integration may cause less damage to the environment. Fig. 4 summarizes the results shown in Fig. 3, considering only the options in which incomes are kept.

For this system, in which the main activity is the production of animal protein (meat or eggs), the interruption of eggs production would improve the environmental performance. The inclusion of a crop plantation may not be the best option in environmental terms as it causes the decrease of both the ESI and the GP values. In a deeper analysis, the main villain both for the integrated and the isolated systems is the quantity of fertilizers required for the crop cultivation, and before install integration the farmer should seek and investigate other alternatives such as agro-ecological

Table 5
Emergy indices of the systems studied; lines in gray show scenarios in which income is maintained. EYR: environmental yield ratio; ELR: environmental load ratio; and ESI: environmental sustainability index.

Scenario	*EYR*	*ELR*	*ESI*
Integrated	1.2 ± 0.1	6.0 ± 0.1	0.2 ± 0.1
No meat	1.3 ± 0.1	4.3 ± 0.1	0.3 ± 0.1
No meat/increasing eggs production	1.2 ± 0.1	6.4 ± 0.1	0.2 ± 0.1
No eggs	1.3 ± 0.1	4.1 ± 0.1	0.3 ± 0.1
No eggs/increasing meat production	1.2 ± 0.1	5.8 ± 0.1	0.2 ± 0.1
No corn	1.2 ± 0.1	5.1 ± 0.1	0.2 ± 0.1
No recycling of animal residued	1.2 ± 0.1	6.4 ± 0.1	0.2 ± 0.1

practices (Fernandez-Mena et al., 2016) or the use of manure (Bi et al., 2020). It is also worthy to note that small plantations distributed among several small integrated systems may help to spread pollution caused by fertilizer use over large areas. The same reasoning may apply to the transport of fertilizers that sometimes come from outside the country, but the lack of a crop plantation would leave the farmer with the animal residues without use and further studies would help decisions on the best environmental use for this resource such biogas production.

This kind of decision, even if results in improvements in the environmental performance of farms in small scale, affects the region in which the agribusiness is inserted in ways that cannot be controlled by the farmers. Regional or national policies are required to identify strategies for achieving the sustainable management of resources and a balanced regional development of rural business, including the creation and maintenance of employment. The challenge remains on sharing and making popular a consistent modeling tool that explicitly represents trade-offs, which trade-off claim for innovative policies in agreement with societal targets (Agostinho et al., 2019). Policy tools funded in scientific analysis could bring together agribusiness integration and territorial strategies, fostering a multifunctional development in which, for example, the fate of animal residues or the centralized provision of animal feed were secured.

4. Conclusions

A new way for using the environmental accounting in emergy was presented to evaluate the environmental sustainability of agribusiness. Seven scenarios were studied in which the existing integrated system was des-integrated to determine the best configuration for the farmer considering the maintenance of his revenues and the best environmental performance. Some results can be highlighted:

- optimizing global productivity and ESI relative to the total amount of protein produced indicates that a system in which egg production is interrupted, but the meat production is increased in 1.89 times would be the most appropriate.
- the use of the residues of the poultry and pig production as organic fertilizer for the corn plantation resulted an advantage for the seven scenarios.
- the increase of systems/processes to be integrated does not guarantee the best environmental performance.

The integrated system promotes sharing of inputs and occurs according to the producer's possibilities and resources, but an hierarchy, which can be of use when designing a new system, was observed. In particular by providing assessments at the farm level, the scenarios

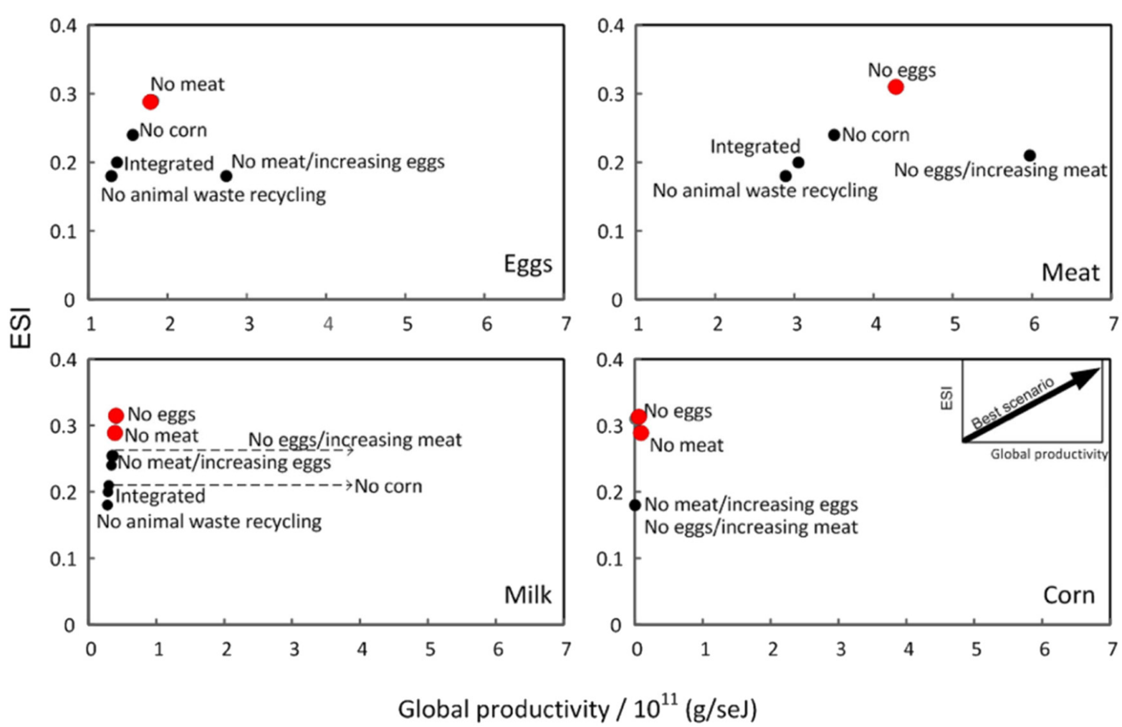

Fig. 3. Environmental Sustainability Index (ESI) versus Global Productivity (grams of protein/seJ) of the eggs, meet, milk and corn: (●) with maintenance of total original revenue and (●) with reduced revenue. The detail in the right bottom shows how to interpret the results.

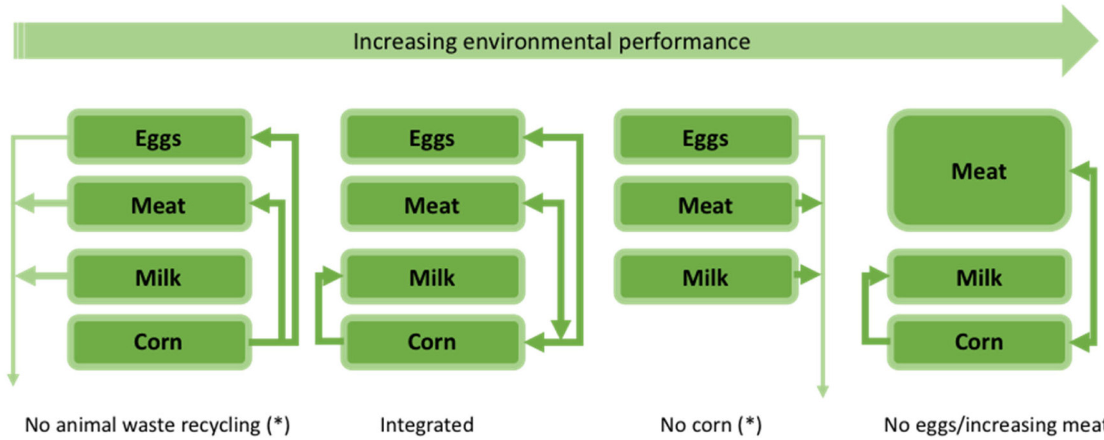

Fig. 4. Summary of the obtained results considering optimizing GP and ESI values. (*) the costs and fate of the animal wastes were not accounted.

presented should help to evaluate organizational innovations and to identify trade-offs that could influence the farm environmental performance.

Through the (des) integration of an agricultural system it was possible to provide a consistent modeling tool that unambiguously represents the trade-offs between the sustainability and productivity and allows transparent discussion to find appropriate solutions to improve the performance of food production systems. In addition, the use of emergy as a modeling tool to optimize agribusiness processes integration led to better understanding of the economic threshold approach (keeping farmer's income) and of the threshold-based management scenarios with varying the number of production processes to be integrated.

Integrated agricultural systems are very similar and have similar opportunities for integration of inputs and output flows. The most popular are crop plantation to feed livestock, animal residues to fertilize the crops, and use of residues – from animal and crops to produce energy. The method proposed brings improved theoretical and policy insights to resources use accounting for agriculture systems, as the agriculture is our main source of food but also a main source of environmental degradation. The emergy evaluation showed to be a tool that can go far beyond the simple integration of agricultural processes and particularly useful in stimulating reflection on widening goals and perspective planning.

Results also show how a single farm can enhance (or not) integration and also stimulate the discussion on how to develop territorial strategies supporting the integration processes between agriculture and other economic activities (such as waste management, animal feed production or biomass-to-energy plants) following a territorial development reasoning. At the same time, key benefits for policymakers and local farmers can also be identified in particular for stimulating convergence of individual actions towards wider regional and local strategic objectives.

CRediT authorship contribution statement

C.M.V.B. Almeida: Conceptualization, Methodology, Supervision. **A.D. Frugoli:**Data curation, Writing - original draft.**F. Agostinho:**Visualization, Investigation, Writing - review & editing.**G.Y. Liu:**Supervision, Writing - review & editing.**B.F. Giannetti:**Writing - review & editing.

Declaration of competing interest

The authors declare that this work has not been published previously (except in the form of an academic thesis - in Portuguese), and it is not under consideration for publication elsewhere. We also declare that we have no conflicts of interest.

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Appendix A. Supplementary data

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