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Integrated crop-livestock systems: A sustainable land-use alternative for food production in the Brazilian Cerrado and Amazon

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ABSTRACT

Sustainable intensification of agriculture is central to deal with the challenges of feeding a growing population while promoting a rational use of environmental and economic resources. Nowhere is this challenge more prominent than in Brazil, where low productivity and environmentally degrading agricultural activities occupy vast areas. We used the emergy synthesis approach, including innovative indices - emergy footprint and carbon-emergy output intensity - to assess and compare the environmental performance of an integrated crop-livestock system to a continuous crop and a continuous livestock system. Our analysis uses survey and empirical case study data from the 2017/18 crop season in Mato Grosso state, Brazil - the largest grain and beef producer in the country. Economic indicators such as gross revenue, production costs and profitability were calculated to complement the sustainability assessments. The emergy indices indicate that integrated crop-livestock system shows a balanced performance between input use and economic and environmental outcomes. In contrast, due to its heavy dependence on external inputs, the cropping system has poor environmental results, but the highest profitability. By excluding these environmental costs, current accounting of soy-corn production in Brazil dramatically overstates its net benefits to society and overall sustainability. The Emergy Sustainability Index for the integrated system was 0.66 and its Net Profit was USD 235.69 ha^{-1}, while for the continuous crop system the values were 0.47 and USD 295 ha^{-1}, respectively. The livestock system performed poorly in both, economic and environmental outcomes, underscoring the need to transition away from existing extensive systems. Livestock shows the highest positive greenhouse gas emissions, 7.98 E−09 $tonCO_{2eq}$ for each joule produced, and Net Loss of USD 0.58 ha^{-1}. These results provide further support for Brazil's

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investment in integrated systems as part of its climate mitigation and sustainable agricultural development plans and warrant consideration in sustainable agriculture initiatives in other countries where cattle production is widespread.

1. Introduction

Ongoing global changes in the interconnections between economic activities and environmental resource use are among the most relevant issues regarding the future of our society. A central challenge in this context is tackling the negative environmental impacts caused by agricultural production and, simultaneously, managing the increasing global demand for agricultural goods and services (Foley et al., 2011; Godfray et al., 2010; Steffen et al., 2015). This is a particularly challenging issue given that agriculture is currently the most extensive land use activity, accounting for 38% of the earth surface, uses more water than any other sector and is the second-largest contributor to the climate change, with 24% of the total global GHG emissions (Davis et al., 2012; FAOSTAT, 2020a; Foley et al., 2011; Han et al., 2019; IPCC, 2013; Tubiello et al., 2015). To meet the increase in global population, forecasted to reach 9.8 billion people by 2050, agricultural production is expected to double (United Nations, 2017).

The widespread adoption of external inputs such as machinery, fertilizers, and pesticides in order to increase productivity in agriculture has enormous implications in the energy used and, as consequence, energy disposal by this activity (Davis et al., 2012; Foley et al., 2011; Odum, 1984). The emergy accounting approach proposed by Howard T. Odum (1996) is an evaluation framework grounded in the hierarchical organization systems and following the irreversible thermodynamics in which the large-scale environmental support for the economy is quantified by computing the values of natural and economic resources on a common basis of energy flow, allowing comparison across different productive systems (Brown, 2004; Brown and Ulgiati, 2004, 1997; Odum, 1996, 1988; Ulgiati et al., 2011). It is particularly useful for evaluating agricultural systems since they rely on the interrelationships between natural and economic inputs to produce goods and services (Barros et al., 2009; Martin et al., 2006; Odum, 1984; Rótolo et al., 2007).

Emergy is defined as the available energy (exergy) of one kind, usually the equivalent solar energy (expressed in solar emjoules - sej), required directly or indirectly to make a product or service (Odum, 1996). It is an estimate of the magnitude of work carried out by nature and society that is embedded in production - the "energy memory" (Brown and Ulgiati, 1997; Odum, 1996; Ulgiati et al., 2011). Emergy synthesis has been widely used to evaluate the efficiency and sustainability of agricultural production systems in different regional contexts, including: i) cropping systems (Barros et al., 2017, 2009; Martin et al., 2006; Ortega et al., 2005; Rótolo et al., 2015; Zhang et al., 2016), ii) livestock (Alfaro-Arguello et al., 2010; Rótolo et al., 2007), and iii) integrated crop-livestock systems (Agostinho and Pereira, 2013; Buller et al., 2015; Cavalett et al., 2006; Fonseca et al., 2016; Lu et al., 2006; Patrizi et al., 2018; Zhai et al., 2017).

In a convergent view, Georgescu-Roegen's contribution to economic theory of production states that matter also exists in two forms: available and unavailable and, similarly to energy, it degrades continuously and irrevocably from the former to the latter (Georgescu-Roegen, 1977). Moreover, Georgescu-Roegen's Fund-Flow model (Georgescu-Roegen, 1970) offers insightful instruments to understand the production process and the interrelationship among goods and services production, assets depreciation and waste generation (Georgescu-Roegen, 1986, 1971, 1970). These approaches are useful to understand land degradation processes produced by large-scale agriculture, particularly the loss of soil quality observed worldwide (Davis et al., 2012; Foley et al., 2011; Graziano da Silva, 2010; Herrero et al., 2010; Reis et al., 2016). The Fund-Flow model divides factors influencing economic activities into two conceptual categories: i) fund factors: assets that transform inflows into outflows - "Ricardian land",[1] human capital, and physical capital and, ii) flow factors: the inputs or outputs that are either produced or consumed during the operation of a system (Georgescu-Roegen, 1970).

To improve the sustainability of agricultural production, it is necessary to expand the use of farming practices and agricultural systems that do not curtail the contribution of the fund factors while, simultaneously, reducing the dependence of external inputs and increasing their efficiency. Moreover, it is necessary to encourage agricultural systems that increase productivity of fund factors, mainly environmental resources, in the short term and allow the growth of their supply in the long run (Ayres, 1993; Daly, 1997; Davis et al., 2012; Ehrlich, 1989; Foley et al., 2011).

The objective of this paper is to evaluate both the environmental and economic performances of agricultural systems in the Brazilian Cerrado and Amazon regions by combining emergy and economic accounting approaches. Our analysis relies on one year of data (2017/18 season), the most up-to-date dataset available, and considers energy flows provided by renewable and non-renewable resources, both internal and external, to the productive systems. The case of the Brazilian Cerrado and Amazon is globally relevant since it is a top producer of many food commodities, including soybean, sugar cane, coffee, orange, corn and beef (FAOSTAT, 2020b). Yet, ongoing commodity growth poses massive environmental challenges. Agriculture and associated land use change, mainly in the Amazon and Cerrado regions, is the largest source of greenhouse emissions and biodiversity loss in the country (Barona et al., 2010; Becker, 2004; Lapola et al., 2014; le Polain de Waroux et al., 2017; Malhi et al., 2008; Nolte et al., 2017; Valentim, 2015).

More specifically, we compare the environmental and economic performances of integrated crop-livestock production, an increasingly popular sustainable intensification strategy in the region, versus conventional continuous crop farming (soybean and corn) and conventional beef cattle production. Integrated crop-livestock systems (iCL) and integrated crop-livestock-forest systems (iCLF)[2] have been posed in agricultural development and national low carbon agriculture plans (Brasil, 2010, 2012a, 2016) as strategies to

[1] The locus in which the productive activity is accomplished (Georgescu-Roegen, 1970; Mueller, 2005).

[2] A survey carried out by Embrapa and ICLF Network in 2017 revealed that 83% of integrated systems in Brazil are integrated crop-livestock systems, 9% are integrated crop-livestock-forest systems, 7% are integrated livestock-forest systems, and only 1% are integrated crop-forest systems (Embrapa; Rede ILPF, 2017). In Mato Grosso, we observe the same pattern of integrated systems' adoption. Therefore, in this paper we will concentrate our analysis in integrated crop-livestock system because this is the integrated system most adopted in Brazil, particularly in Brazilian Cerrado and the Amazon region.

reduce both direct emissions and emissions from deforestation, by increasing land productivity and diversifying production (Franzluebbers, 2007; Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016). These agricultural systems aim to improve production sustainability through the integration of various types of agricultural production (i.e. crops, livestock and forestry) in the same area, via intercropping, or rotations, to obtain synergies among agroecosystem components (Balbino et al., 2011; Lemaire et al., 2014; Macedo, 2009; Nair, 1991). Moreover, integrated systems, mainly iCL, can favor the reclamation of degraded pastures (Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011) through crop residual fertility and application of crop revenues to restore soil quality and fund further system improvements (Costa et al., 2012; Vilela et al., 2011).

However, information about iCL systems as a feasible alternative to large-scale continuous crop and livestock systems in the Cerrado and Amazon is limited, mainly, analysis considering the requirements for energy of these systems and the implications of these land-use strategies for the long-run sustainability. Recent research in this area includes Buller et al. (2015), which assessed integrated swine, crop, pasture and eucalyptus in the Cerrado-Pantanal ecotone and Costa et al. (2018), who examined integrated and non-integrated combinations of annual crops (soy, corn, and sorghum), forestry (eucalyptus for energy supply), and cattle production systems in Brazilian Cerrado. Buller et al. (2015) used a modified emergy assessment that included GHG emission accounting, while Costa et al. (2018) used a Life Cycle Assessment (LCA) approach. Both studies found that iCL systems provide environmental, economic, and social benefits relative to continuous cropping or livestock production. However, both studies are based on experimental farms and small areas that do not adequately represent large-scale commercial commodity production systems in the Cerrado and Amazon regions. Moreover, the economic assessment provided by Costa et al. (2018) was based only on production costs, limiting our understanding of the economic outcomes of such systems. More broadly, several other studies have only evaluated the environment (Agostinho and Ortega, 2012; Buller et al., 2015; Cavalett et al., 2006; Salton et al., 2014) and/or economic outcomes of iCLs (Costa et al., 2012; dos Reis et al., 2019; Gil et al., 2018; Lazzarotto et al., 2010), but have not synthesized them in comparable energy terms.

The present work innovates on the existing literature by providing a comprehensive analysis of both the energy and economic flows of the three most common commercial crop and livestock systems observed in the Cerrado and Amazon and provides results for two innovative emergy indices: emergy footprint (Agostinho and Pereira, 2013; Björklund and Johansson, 2013; Wright and Ostergård, 2016) and carbon-emergy output intensity (Dong et al., 2018). Given the region's importance for global food security and environmental change, the results may be a critically important test case for understanding the potential of agricultural intensification to tackle major sustainability challenges.

2. Methods

2.1. Study region

The analysis focuses on comparing typical crop and livestock farms from two different regions - Mid-North and Southeast - of the state of Mato Grosso in Brazil, elaborated using survey data from Mato Grosso Institute of Agricultural Economics (IMEA) (IMEA, 2020), and a case study data from an integrated crop-livestock farm located in the municipality of Santa Carmen, in the Mid-North region of Mato Grosso. The cropping data were gathered from the municipality of Sorriso (Fig. 1a), which produces around 40% of all soybeans and corn in the state of Mato Grosso. The livestock data were obtained from the municipality of Barra do Garças (Fig. 1b), which contains about 16% of the total cattle herd in Mato Grosso (IBGE, 2020).

Mato Grosso is one of the largest and most productive agricultural frontiers in the world (IBGE, 2020; IMEA, 2020; MAPA, 2020), spans three ecological biomes: the Amazon, Cerrado, and Pantanal. It produces 28% of the soybeans, 33% of the corn, and 71% of the cotton cultivated in Brazil, an area of 11 million hectares (IMEA, 2020). Furthermore, it contains 15% of Brazilian beef cattle herd, 30.1 million heads, on an area of 23 million hectares (IBGE, 2020; IMEA, 2020).

The production is associated with considerable negative environmental impacts, particularly deforestation (Andersen et al., 2002; Barona et al., 2010; Hargrave and Kis-Katos, 2013; Malhi et al., 2008). Mato Grosso has among the highest rates of deforestation in the Amazon region - only in 2019, 1685 Km^2 were deforested in Mato Grosso (INPE, 2020) -, which is driven largely by extensive cattle ranching practices (Macedo et al., 2012; Malhi et al., 2008; Margulis, 2003). iCL has been proposed as a major land sparing strategy for the region alongside the introduction of zero-deforestation policies (Brasil, 2016, 2012a; Nepstad et al., 2019).

2.2. Systems description

The characterization of the "typical" conventional crop and livestock farms for the 2017/18 season were developed using: i) farm observations; ii) meetings with local stakeholders including farmers, retailers, technicians, consultants, trading managers, and; iii) data from IMEA (IMEA, 2020). The meetings were used to collect and systematize information on the most common farming systems in the state, including: i) farm areas; ii) infrastructure and technology adoption; iii) management practices; iv) production costs; v) average yields; and vi) labor use.

The typical crop farm is defined as an intensive and specialized production system with soybean-corn continuous rotation in 1200 ha of land area. Soybean (*Glycine max*) being cultivated from October to February and corn (*Zea mays*) from February to June/July. This farm possesses a high level of technology with large investments in infrastructure and inputs. The initial investment[3] required for the operation of this continuous soybean-corn rotation was 1196.11 USD. ha^{-1}, excluding land acquisition costs. The large investment in technology results in high productivity: 3.6 tonnes ha^{-1}. $year^{-1}$ of soybean and 6.7 tonnes. ha^{-1}. $year^{-1}$ of corn, and production costs as high as 997.77 USD. ha^{-1}. Most soybean and corn production are exported through multinational traders.

In contrast, the typical livestock farm is a traditional cattle ranch with low levels of technology, low productivity, and large land areas. Typical livestock farm size is 2200 ha of pastures, managed to complete the full cycle of production: breeding, rearing, and fattening. Traditional cattle ranchers do not invest in elaborated infrastructure, only in basic equipment such as corral, troughs, and fences. Also, they do not invest in intensive pasture management. As a consequence, there have difficulties providing adequate nutrition to the herds in dry season. The most common cattle breed is Nelore (*Bos taurus indicus*), and the pasture grass is *Urochloa brizantha*. Productivity of the traditional livestock farm is 159.9 kg ha^{-1}. $year^{-1}$, and the initial investment required for its operation is 215.01 USD. ha^{-1}, also excluding land acquisition costs.

[3] 2018 prices (1 USD = 3.65 REAIS). Conversion using exchange data from official Brazilian Govern database provided by Research Institute of Economic Applied (IPEA): http://www.ipeadata.gov.br/Default.aspx. This exchange rate was applied in all monetary values presented in this paper.

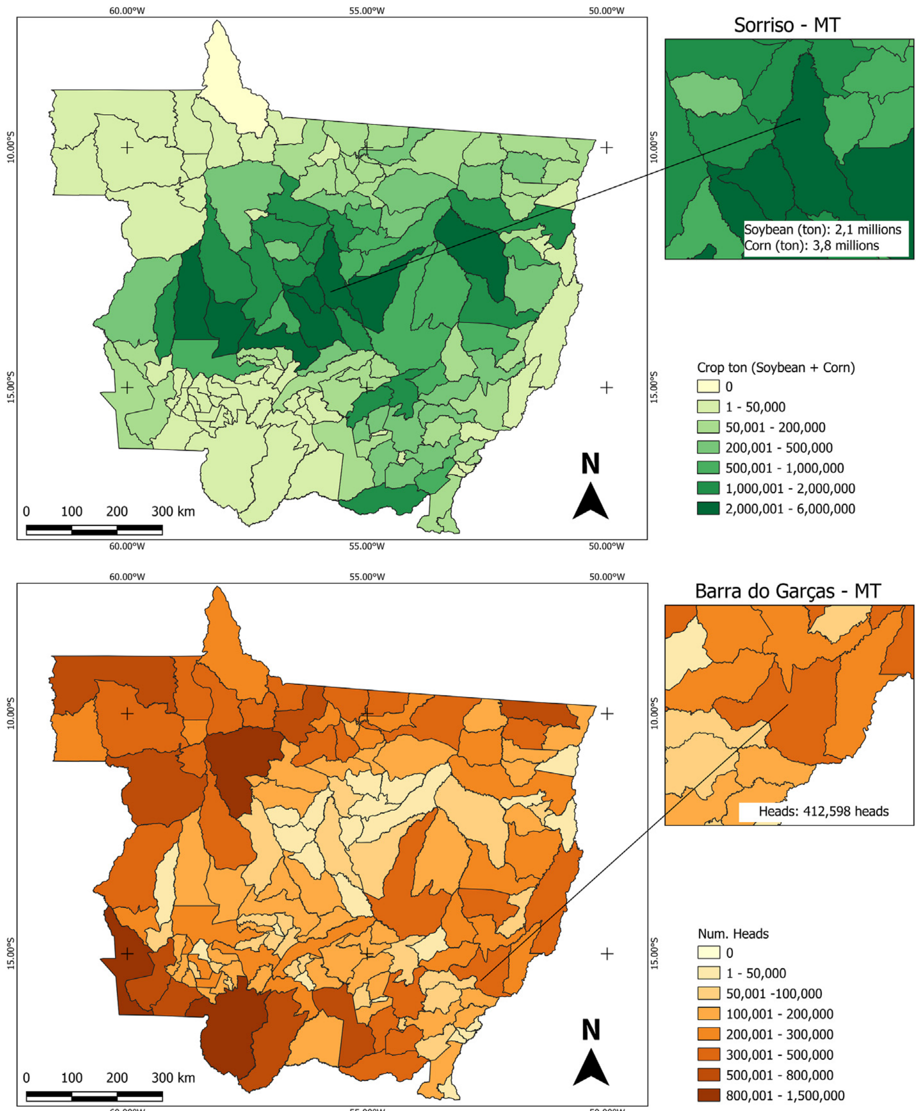

Fig. 1a. Crop concentration in Mato Grosso (2017) Fig. 1b - Livestock concentration in Mato Grosso (2017

Its annual production cost is 165.93 USD. ha^{-1}.

The integrated crop-livestock farm used in this analysis (Fazenda Platina) is located in the municipality of Santa Carmen, in the Mid-North region of Mato Grosso. The farm has 2678 ha of cultivated land. The initial investment was 877.04 USD. ha^{-1}, and production cost for 2017/18 was 503.19 USD. ha^{-1}. The annual land-use management follows this general guideline: between October and February, 1078 ha cultivated with soybean and the remaining area is used for cattle maintenance. After harvesting soybean, the whole farm is turned to livestock production. The livestock system is managed to complete the full cycle of production: breeding, rearing, and fattening.

The animals are sold for slaughter when they reach 585 kg. Supplements are used all year long and included: i) mineral salt for breeding stock with an average consumption ranging between 67 and 100 g. day^{-1} and 100 and 150 g. day^{-1} according to animal weight in the rainy and dry season, respectively; ii) a ratio of 300g to each 100 kg of live weight of cattle feed in the rearing stage and; iii) 8.9 kg. day^{-1} of cattle feed in the fattening stage. Mangers for feed supplementation and watering were adequately available throughout the farm area.

2.3. Emergy approach

The emergy approach is a conceptual framework that offers tools to evaluate the contributions of environmental services (a donor-side perspective) that, in general, are not considered in the traditional economic analysis of production, which is based on an user-side perspective (Brown and Ulgiati, 2004, 1997; Odum, 1996, 1988), and provides a measure on the extent through which the productive activities rely on biophysical support (Brown and Ulgiati, 2004). The evaluation process is carried out by multiplying all inputs used in the evaluated production system by a correspondent unit emergy value (UEV) (Brown and Ulgiati, 2004). The UEV expresses the 'solar emergy joules' (sej) used up to create a unit of a product or service. It expresses the amount of energy of one type required to generate a unit of energy of another type (Odum, 1996).

The boundaries of the systems, as well as the connections among all resources used in the three production systems are represented in diagrams based on the energy system language (Fig. 2) (Brown, 2004; Odum, 1996).

A quantitative representation of most relevant resources for the three agricultural systems: local renewable resources (R), local non-renewable resources (N), purchased resources (F), and outputs (Y), as well as their UEVs, are listed in (Table 2). The emergy synthesis was performed considering one cropping season (2017/2018), the most recently available information. To provide comparable results, the inputs and the outputs were normalized for ha^{-1}. year $^{-1}$. The baseline used was 12.1 E+24 sej. year^{-1} (Brown et al., 2016).

Emergy literature offers a set of indices based on the relationship among all energy sources used in the production process to evaluate the performance of each system. The emergy indices can be used to demonstrate the thermodynamic efficiency of the productive process, the quality of its output, and the interrelationship between the economic activities and their surrounding environment (Brown and Ulgiati, 1997). These indices can be viewed as useful decision tools about short-run and long-run sustainability of productive systems since their focus on central sustainable production issues, for instance: i) the net yield; ii) an environmental load of production, and iii) the use of non-renewable resources (Brown and Ulgiati, 1997; Odum, 1996; Ulgiati et al., 2011). The indices used are summarized in (Table 1). All input flow data and index calculations were carried out using SAMeFrame (Rodrigues et al., 2002) and are available in the supplemental material.

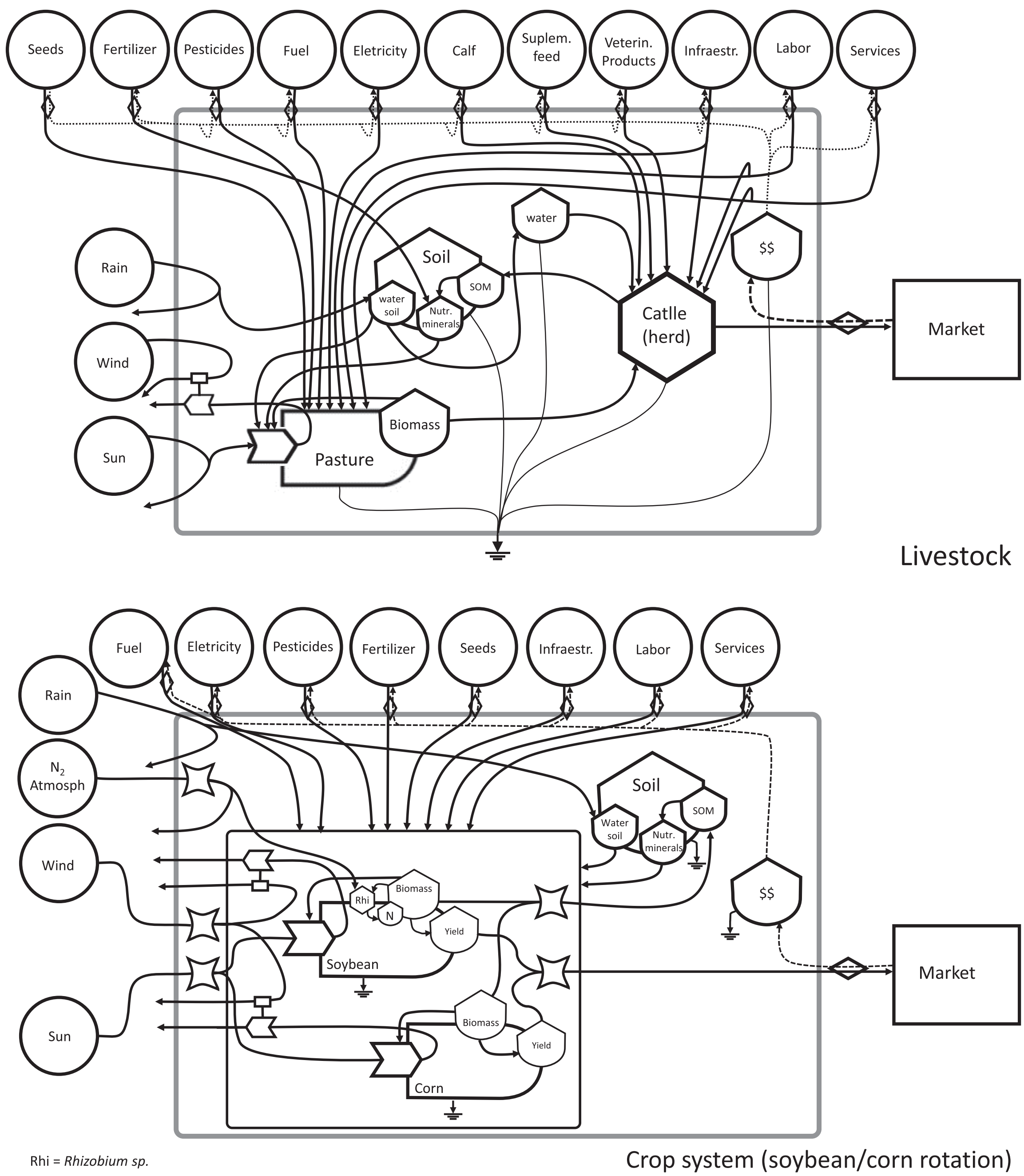

Fig. 2. Energy flow diagrams.

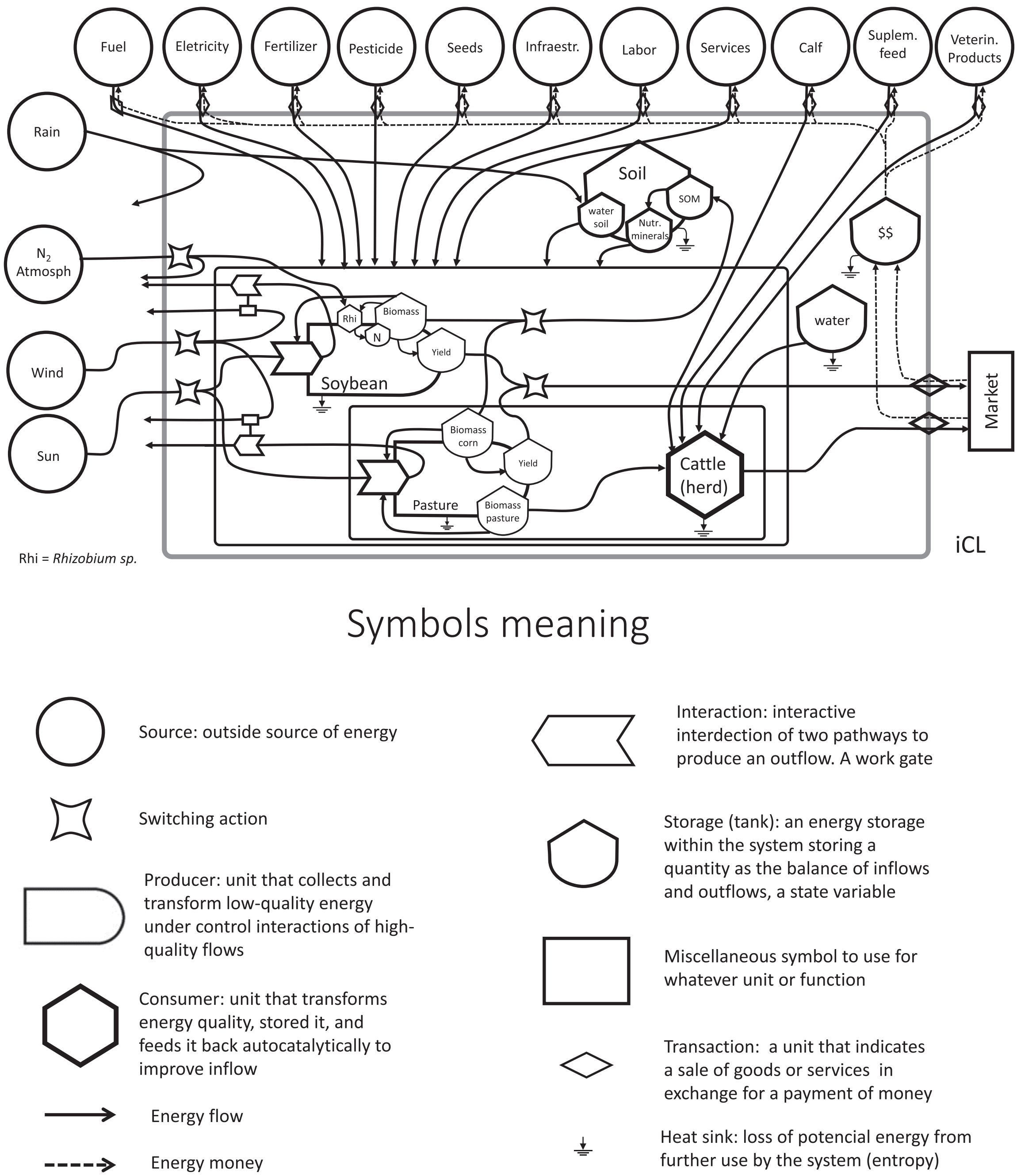

Fig. 2. (*continued*).

2.4. Economic assessment

We used economic accounting analysis approach to compare the economic results of the three agricultural systems. This method is established in the economic literature as an instrument to evaluate the economic potential of any productive activity (Buarque, 1984; Gitman and Zutter, 2014; Lapponi, 2013). We calculated Gross Revenue, Net Revenue, Production Cost and Net Profit. Commercialization prices observed in Mato Grosso for 2017/18 season for all products were provided by IMEA (IMEA, 2020). To calculate Net Profit, we used a comprehensive approach considering operational, administrative, financial and fiscal taxes. Data used for economic analysis are on supplementary material.

3. Results

3.1. Renewable resources

Rainfall is a critical natural renewable resource for agricultural production. Mato Grosso receives high yearly precipitation, but has a marked dry season from June to September. Hence, management of agricultural systems to make the best use of this resource are decisive for good environmental performance. To avoid double-counting, evapotranspiration was accounted as the net productive portion of the biophysical inputs: sunlight, rain geopotential, wind, and Earth cycle, since all of them are by-products of the same coupled process of dissipation of sunlight energy (Barros et al.,

Table 1
Emergy indices.

Indicators	Formula	Definition	Outcome
Transformity (Tr)	$\frac{E}{Y}$	The ratio of emergy in a product to the remaining available energy (exergy)	It is an indicator of the efficiency of the production process.
Percentage of Renewable Resource (%R)	$\frac{R}{(R+N+F)}$	Percentage of the total energy used that is from a renewable resource	In the long run, systems with higher renewable resource percentage tend to be more sustainable
Emergy Yield Ratio (EYR)	$\frac{Y}{F}$	The relation between the emergy of output and that is fed back from the outside productive system	This index evidences the system's net contribution to the economy
Environmental Load Ratio (ELR)	$\frac{(N+F)}{R}$	The relation between the set of nonrenewable resources and renewable resources	It is a measure of the ecosystem stress due to production activity
Emergy Investment Ratio (EIR)	$\frac{F}{(R+N)}$	The relation between free environmental inputs and external inputs used	This index illustrates the system dependency of external resources (economic system)
Environmental Sustainable Index (ESI)	$\frac{EYR}{ELR}$	The ratio between yield and environmental load	Sustainable systems are not based only in low requirements of F but, also, in the higher relation R/(F + N)
Emergy Footprint[1]	$A_{renew} + A_{non-renew}$	Indicates the theoretical area needed if local renewable resources generated all resources used in a production system	Systems with higher emergy footprint present a higher environmental load
Carbon-emergy output intensity (CemI)[2]	$\frac{CO_{2-eq}}{Y}$	Net ton $CO_{2\text{-eq}}$ emissions per unit yields measured in emergy	Sustainable systems contribute to reduce $CO_{2\text{-eq}}$ emissions

Source: (Brown and Ulgiati, 1997; Dong et al., 2018; Odum, 1996; Wright and Østergård, 2016)
[1]A detailed explanation of Emf formalization and calculations are in the supplementary material.
[2]A detailed explanation about CemI formalization and calculations are in the supplementary material.

2009; Martin et al., 2006; Odum, 1996). The differences across the three production systems are remarkable. Evapotranspiration represents 25.9% (110.6 E+13 sej. year^{-1}) of the total emergy used by the integrated systems, 15.1% (71.5 E+13 sej. year^{-1}) by the crop system and 65.6% (113.7 E+13 sej. year^{-1}) by the livestock system. This number illustrates traditional cattle ranching's heavy reliance on renewable resources.

Another important renewable resource is atmospheric nitrogen (N_2) fixation provided by soybean. This biological feature of soybean production is essential to reduce nitrogen (N)-fertilizer uses and helps to explain the extensive use of this crop in the Cerrado over the last 30 years. N_2 atmospheric fixation represents 10.1% (47.9 E+13 sej. year^{-1}) of crop system emergy uses and 5.3% (22.5 E+13 sej. year^{-1}) for the integrated system. This contribution is absent from the livestock system entirely.

3.2. Non-renewable resources

The non-renewable resource considered for all three systems is topsoil losses. The estimated topsoil losses were: 1509.5 kg ha^{-1} for crop system, 898.3 kg ha^{-1} for the integrated system, and 287 kg ha^{-1} for the livestock system.

3.3. Purchased resources

There were large differences in dependence on externally purchased resources among the three production systems. The crop production system showed the highest value for the purchased input set: 73.7% of all emergy used. Fertilizers and limestone represented the most important share of these external inputs: 48.2%. The amount of limestone used in the crop system 679.6 kg ha^{-1} was similar to the value for the integrated system 592.0 kg ha^{-1}. However, the amount of mineral nutrients[4] in fertilizers was much higher. Crop systems used 201.2 kg ha^{-1} of mineral nutrients, whereas the integrated system used only 68.3 kg ha^{-1}. The values for the traditional livestock system were rather small: 186.6 kg ha^{-1} of limestone and only 2.4 kg ha^{-1} of mineral nutrients.

Although it represented only 3.3% of total emergy used in the crop system (15.7 E+13 sej. year^{-1}) or 13.9 kg ha^{-1}, the amount of pesticides in the crop system was three times higher than the value observed in the integrated system (5.1 E+13 sej. year^{-1}) or 4.5 kg ha^{-1}. The values for fuel consumption showed the crop system's heavy reliance on fossil fuel and machinery inputs. The fuel consumption of the crop system was (14.4 E+13 sej. year^{-1}) or 3.1% of all emergy used. In contrast, the value for the integrated system was four times smaller (3.7 E+13 sej. year^{-1}), representing only 0.9% of the total emergy. The fuel consumption value for the livestock system was the lowest, only (1.3 E+13 sej. year^{-1}) or 0.7% of total emergy used.

In the integrated system, besides limestone and fertilizer, two other inputs presented substantial values: steers with (5.8 E+13 sej. year^{-1}), 1.4% of all emergy used, and calves (40.9 E+13 sej. year^{-1}), 9.6% of all emergy. These are the major inputs for livestock in the integrated system. In this system grazing is complemented with animal feed, and this input accounted for a sizable share of emergy use (46.1 E+13 sej. year^{-1}) or 10.8%. The intensive supplement feed associated with highly nutritive pasture in the integrated system explains the striking productivity difference between this system (280.7 kg of live weight ha^{-1}) and the traditional livestock system (159.9 kg of live weight ha^{-1}).

For the livestock system, steers were the sole category of animal acquired. The values found (3.9 E+13 sej. year^{-1}) were 2.3% of all emergy used. As a consequence of the low technology level, the only supplement feed used is mineral salt, which reached 3.2% of all emergy used or (5.5 E+13 sej. year^{-1}). Another feature that illustrates the lower technology level of livestock is its higher value for labor use. This input represented 2.8% of all emergy used in the livestock activity. In contrast, labor represented 1.1% in the integrated system and 1.2% in the crop system.

Finally, the result for services and infrastructure inputs, composed mainly of taxes, administrative costs, and post-harvest services, displays the relevance of external economic resources for the crop system. The values, considered in emergy currency (emdollar) for the crop system (64.2 E+13 sej. year^{-1}) were more than twice the value for the integrated system (25.6 E+13 sej. year^{-1}) and ten times larger than for the livestock system (5.0 E+13 sej. year^{-1}).

[4] In this analysis, mineral nutrient set is formed by: Nitrogen, Phosphorus, Potassium.

Table 2
Inputs, UEVs and results.

			Data (units/yr)					Solar Emergy (E+13 sej/yr)		
Note	Item	RawUnit	ICL	Crop	Livestock	UEV (sej/unit)[a]	Ref.[b]	ICL	Crop	Livestock
Renewable resources (R)										
1	Sunlight	J	5.24E+13	5.40E+13	6.01E+13	1.00E+00	[1]	5.24	5.40	6.01
2	Rain, geopotential	J	5.08E+10	5.42E+10	7.32E+09	3.57E+04	[3]	181.31	193.57	26.15
3	Wind, kinetic energy	J	1.30E+10	4.19E+09	3.65E+09	1.86E+03	[3]	2.42	0.78	0.68
4	Et (Rain, chemical potential)	J	5.62E+10	3.63E+10	5.77E+10	1.97E+04	[2]	110.61	71.50	113.72
5	Earth cycle	J	1.45E+10	1.45E+10	1.45E+10	9.12E+03	[3]	13.22	13.22	13.22
6	N_2 atmospheric fixation	J	1.04E+05	2.22E+05	0.00E+00	2.16E+09	[4]	22.56	47.93	0.00
Nonrenewable storages (N)										
7	Topsoil losses	J	7.63E+08	9.38E+08	1.35E+08	5.62E+04	[5]	4.29	5.28	0.76
	Sum of free inputs (wdc)							**137.46**	**124.71**	**114.48**
Purchased inputs (F)										
8	Fuel	J	4.44E+08	1.72E+09	1.52E+08	8.43E+04	[2]	3.74	14.46	1.28
9	Electricity	J	1.19E+08	2.92E+08	1.15E+08	2.55E+05	[2]	3.04	7.47	2.93
10	Limestone and fertilizers	g	6.60E+05	8.81E+05	1.89E+05	1.55E+09	[2]	140.36	228.37	29.31
11	Pesticides	g	4.52E+03	1.40E+04	5.10E+02	1.12E+10	[6]	5.09	15.72	0.57
12	Seeds (Soybean)	g	4.80E+04	3.50E+04	0.00E+00	1.38E+09	[7]	6.64	4.84	0.00
13	Seeds (Corn)	g	0.00E+00	1.50E+04	0.00E+00	1.50E+09	[9]	0.00	2.26	0.00
14	Seeds (Pasture)	J	5.16E+07	7.36E+07	7.22E+06	2.89E+05	[8]	1.49	2.13	0.21
15	Steers (Bulls)	J	4.27E+07	0.00E+00	2.89E+07	1.37E+06	[8]	5.85	0.00	3.96
16	Calves	J	1.85E+08	0.00E+00	0.00E+00	2.21E+06	[8]	40.94	0.00	0.00
17	Supplement feed (minerals)	g	1.58E+04	0.00E+00	7.27E+04	7.60E+08	[7]	1.20	0.00	5.53
18	Supplement feed (fodder)	g	3.34E+05	0.00E+00	0.00E+00	1.38E+09	[7]	46.15	0.00	0.00
19	Management and reproduction	$	7.12E+00	0.00E+00	8.97E+00	4.26E+12	[10]	3.04	0.00	3.82
20	Mechanical equipment	g	2.43E+03	4.58E+03	1.59E+03	8.58E+09	[5]	2.08	3.93	1.36
21	Labor	J	7.88E+06	1.02E+07	8.39E+06	5.75E+06	[6]	4.53	5.84	4.82
22	Services, infrastructure	$	6.02E+01	1.51E+02	1.18E+01	4.26E+12	[10]	25.66	64.28	5.04
	Sum of purchased inputs							**289.80**	**349.30**	**58.83**
Total emergy								**427.26**	**474.01**	**173.31**
Production (Y)										
23	Total Yield, dry weight	g	1.61E+06	7.78E+06	4.80E+04					
24	Total Yield	J	3.31E+10	1.60E+11	9.88E+08					

[a] : Unit Emergy Value. Baseline 12.1 E24 sej/year (Brown et al., 2016).
[b] : [1] by definition; [2] Odum (1996); [3] Odum et al. (2000); [4] Campbell et al. (2014); [5] Brown and Bardi (2001); [6] Brandt-Willians (2001); [7] Castelinni (2006); [8] Rótolo (2007); [9] Rótolo (2015); [10] Giannetti (2018).

3.4. Emergy indices

The results for the set of indicators show a striking contrast between the crop system, heavily dependent on purchased external inputs (a renewable resource use of 25%), and the cattle system, based largely on free local resources (a renewable resource use of 66%). The integrated system is in between, using quite a few external inputs, but also capitalizing on free renewable resources (a renewable resource use of 31%)

The small portion of renewable resources used explains the higher Environmental Load Ratio (ELR) for the crop system: 2.97. The ELR for the integrated system was 2.21, and for the livestock system 0.52. These results indicate that the crop system poses higher ecosystem stress than the other productive activities. The high investment in external inputs as a strategy to capture renewable resources from the environment in the crop system is not as efficient as in the integrated system. The Emergy Investment Ratio (EIR) for the crop system was 2.80, and for the integrated system it was 2.11. The best performance considering investment on external inputs was in the livestock, which presented the value of 0.51 for the EIR.

The Emergy Yield Ratio (EYR) results demonstrate the net contribution to the economy from the productive systems. The crop system, even displaying higher productivity, presented the lesser

Table 3
Emergy indices results.

Indicators	Formulas	ICL	Crop	Livestock
% Renewable	**R/(R + N + F)**	0.31	0.25	0.66
Environmental Loading Ratio	**(F + N)/R**	2.21	2.97	0.52
Emergy Investment Ratio	**(F)/(N + R)**	2.11	2.80	0.51
Emergy Yield Ratio	**Y/(F)**	1.47	1.36	2.95
Non-renewable/Renewable	**(N + F)/R**	2.02	2.43	0.48
Empower Density	**sej/ha/yr**	4.27E+15	4.74E+15	1.73E+15
Emergy Sustainability Index	**EYR/ELR**	0.67	0.46	5.62
Transformity		1.29E+05	2.96E+04	1.75E+06
Emergy Footprint		8592.57	4762.57	3352.87
EmF (factor m)		3.21	3.97	1.52
CemI	**ton CO2eq/Y (J)**	−2.71E-11	3.70E-11	7.98E-09

performance. The EYR for the crop system was 1.36, whereas the value for the integrated system was 1.47 and for the livestock system 2.95. The comparatively higher value for the livestock is due to its smallest use of external inputs. Taking into account the results for the EYR and the ELR, the Environmental Sustainable Index (ESI) illustrates as the crop system presents an unbalanced performance, considering the economic and the ecological sub-systems. The value of 0.46 emphasizes the importance of external inputs for the crop system and the smaller relation R/(F + N) for this productive system. An opposite result is showed by the livestock system, with an ESI of 5.62. The ESI for the integrated system was 0.67.

The emergy footprint values highlight the heaviest environmental load for the crop system. If local renewable resources provided all emergy used in this activity, the farm area would need to be almost four times larger than its real size. In contrast, the emergy footprint for the livestock system indicated that an area 52% larger would be sufficient to provide all emergy used in this activity. For the integrated system, the area needed to provide all emergy used would be 3.2 times larger than its real size.

Lastly, the carbon-emergy indices show the potential of the iCL system to mitigate emissions of greenhouse gases from agriculture. According to our results, integrated systems displayed an emission factor of −2.71 E−11 $tonCO_{2eq}$ for each joule produced. In contrast, the crop system released 3.70 E−11 $tonCO_{2eq}$ for each joule produced. The traditional livestock demonstrated the worst performance. This system shows a positive emission of 7.98 E−09 $tonCO_{2eq}$ for each joule produced.

3.5. Economic results

The high productivity and elevated prices for corn and soybean explain the larger profitability observed for the crop system, which presented net revenue 79% higher than the integrated system and eight times higher than the traditional livestock system. Even displaying higher production costs, mainly because of purchased inputs that represented 87% of the total production cost, the crop system presented the best economic performance. This system presented a net profit of 295.00 USD ha^{-1}. In contrast, the livestock system showed a net loss of 0.58 USD ha^{-1}, while the integrated system a net profit of 235.69 USD ha^{-1} (table 4).

4. Discussion

4.1. Cropping is an energy-intensive system

The continuous cropping systems produce a high net yield. However, its higher reliance on external inputs and higher UEVs values for its main inputs such as fertilizers, pesticides, and seeds lead to a greater impact on the environment. A higher UEV value of a resource is related to a greater environmental activity necessary to produce it (Brown and Ulgiati, 1997; Odum, 1996, 1988). Moreover, since higher UEV expresses relative scarcity (Brown and Ulgiati, 2004; Odum, 1996), these inputs tend to be pricier, which explains the higher production cost observed for the crop system, 98% higher than the integrated system. High external input needs result in high costs, which leads to a vicious circle, whereby higher productivity is sought to offset the high production costs, leading to even greater external input use.

The negative environmental impacts of continuous cropping have already been reported in the existing literature (Barros et al., 2017; Costa et al., 2018; Martin et al., 2006; Ortega et al., 2005; Rótolo et al., 2015; Zhang et al., 2016). Similarly, the improved environmental performance of integrated systems has already been observed in previous studies (Buller et al., 2015; Cavalett et al., 2006; Costa et al., 2018; Fonseca et al., 2016; Patrizi et al., 2018). What our findings highlight is that: i) the overall impacts, as measured by emergy indices, are substantially lower in an integrated system versus a continuous system, while still producing high amounts of food, and ii) given the combination of high economic and environmental costs, specialized cropping may be producing net negative benefits to society and is not a sustainable prospect for the Cerrado and Amazon region (Martin et al., 2006; Ortega et al., 2005; Rótolo et al., 2015).

4.2. Integrated systems can improve the efficiency of the fund factors

The highest soybean productivity observed in the integrated system (4.2 tonnes. ha^{-1}) was reached using three times fewer fertilizers than the crop system, which had a productivity of only 3.6 tonnes. ha^{-1}. This is likely due to the management strategy in integrated systems - a rotation of soybean and pasture − which

Table 4
Economic results.

Integrated Crop- Livestock		Crop System		Livestock System	
(+) Gross Revenue	852.44	(+) Gross Revenue	1513.12	(+) Gross Revenue	196.44
Soybean	488.23	Soybean	1025.92	Livestock	196.44
Livestock	364.20	Corn	487.20		
(−) Sales taxes	39.73	(−) Sales taxes	56.29	(−) Sales taxes	10.36
(=) Net Revenue (A)	**812.70**	**(=) Net Revenue (A)**	**1456.83**	**(=) Net Revenue (A)**	**186.08**
(−) Input Costs	**433.85**	**(−) Input Costs**	866.56	**(−) Input Costs**	**76.13**
Soybean	249.18	Soybean	610.05	Livestock	76.13
Livestock	184.68	Corn	256.50		
(−) Machinery and Infrastructure	**24.11**	**(−) Machinery and Infrastructure**	77.69	**(−) Machinery and Infrastructure**	**64.06**
Fuel and lubricants	9.43	Fuel and lubricants	37.93	Fuel and lubricants	59.66
Maintenance	14.68	Maintenance	39.77	Maintenance	4.40
(−) Labor	**45.23**	**(−) Labor**	53.52	**(−) Labor**	**25.75**
Permanent Workforce	45.23	Permanent Workforce	48.14	Permanent Workforce	25.35
Temporary employment		Temporary employment		Temporary employment	0.40
(=) Total Cost (B)	**503.19**	**(=) Total Cost (B)**	**997.77**	**(=) Total Cost (B)**	**165.93**
(=) Gross Profit (A−B)	**309.51**	**(=) Gross Profit (A−B)**	**459.06**	**(=) Gross Profit (A−B)**	**20.15**
(−) Expenses	**24.85**	**(−) Expenses**	**85.06**	**(−) Expenses**	**8.11**
General: energy and administrative	8.42	General: energy and administrative	19.13	General: energy and administrative	
Post-harvest	16.43	Post-harvest	65.93		
(=) EBITDA*	**284.66**	**(=) EBITDA***	**373.99**	**(=) EBITDA***	**12.04**
(−) Depreciation and Amortization	**48.97**	**(−) Depreciation and Amortization**	**79.00**	(−) Depreciation and Amortization	12.61
(=) Net Profit	**235.69**	**(=) Net Profit**	**295.00**	**(=) Net Profit**	**−0.58**

[a] EBITDA = Earning Before Interests, Taxes, Depreciation and Amortization. This indicator shows the operational cash flow.

contributes to an increase soil organic matter content and, consequently, soil fertility (Costa et al., 2018; Franzluebbers et al., 2014; Franzluebbers and Stuedemann, 2008; Oliveira et al., 2018). Soil analyses indicated a 3.67 gr. kg^{-1} average of organic matter in the integrated system, while the value for the crop system was 2.75 gr. kg^{-1} (25% lower).

This improvement in the fund factor (the soil) lessens the need for flow factors (soil correctives and fertilizers). Conversely, the extensive use of external inputs in the cropping system to increase productivity creates additional demand for free inputs degrading the fund factors (Davis et al., 2012; Martin et al., 2006; Martinelli et al., 2010). The negative consequences can be viewed most prominently in the case of soil services. Since the soils' services used are not replaced by the large-scale continuous crop activity, at least as fast as their use rate, the result is soil degradation (Davis et al., 2012; Ehrlich, 1989; Foley et al., 2011). The crop system topsoil losses are around twice those for the integrated system, and five times higher than the observed for livestock. These values are aligned with a recent meta-analysis for soil erosion in Brazil (Anache et al., 2017). This too stimulates a vicious cycle. To maintain and increase productivity in light of decreasing soil quality, the continuous crop systems may require increased fertilizer inputs, further reducing the environmental and economic performances of the system.

In contrast, the integrated system results suggest that the continued crop-livestock rotation has the potential to increase soil organic matter (Costa et al., 2018; Franzluebbers et al., 2014; Franzluebbers and Stuedemann, 2008; Herrero et al., 2010; Oliveira et al., 2018). By improving or, at least, maintaining soil fertility and, at the same time, providing better productivity performance, the integrated systems enhance the productivity of fund factor soil in the short term, and its productive services supply in the long-run, encouraging a more efficient use of environmental resources and more sustainable agricultural practices (Daly, 1997; Davis et al., 2012; Foley et al., 2011; Herrero et al., 2010; Reis et al., 2016).

4.3. Synthesizing the economic and emergy results reveals the unsustainable contributions of nature to the current agricultural systems

A significant advantage of emergy synthesis is to evaluate contributions from nature and people in common units (Brown and Ulgiati, 2004; Odum, 1996, 1988). Moreover, since the economic subsystem pays only people for their services and not the environment for its work (Odum, 1996), the traditional economic evaluation provides incomplete results about the potential of activities to generate real wealth (Brown and Ulgiati, 2004; Odum, 1996).

The economic results observed for the three agricultural systems studied highlight this issue. Even with the highest production costs (977.77 USD. ha^{-1}), the net profit for the crop system (295 USD. ha^{-1}) was 25% higher than the profit of the integrated system and incomparably higher than the livestock system, which show a net loss of 0.58 USD. ha^{-1}. These results would suggest that the crop system is the best alternative for farmers to invest their money. The economic results for the crop system are due to its high productivity and the high prices for corn and, mainly, soybean in the 2017/18 season (IMEA, 2020) (Graph 1).

Nonetheless, the economic results contradict the observed outcomes provided by the emergy synthesis approach once the economic analysis does not take into account the contribution from environmental resources (Odum, 1996). The crop system uses a considerable amount of external purchased inputs to capture environmental resources services (Martin et al., 2006; Rótolo et al., 2015). The high efficiency of external inputs and the large-scale production explain the positive performance of the economic subsystem. However, this pattern is unsustainable. The emergy results highlighted the environmental stress caused by crop system and its contribution to deteriorating environmental conditions, as indicated by the ELR, ESI and Emf indices.

4.4. Land sparing and CO_2eq sequestration in the integrated crop-livestock systems

The adoption of more productive agricultural systems may help offset pressures to expand agricultural areas into forests in the Cerrado and Amazon regions (Barona et al., 2010; Becker, 2004; Lapola et al., 2014; Nolte et al., 2013; Strassburg et al., 2014). The emergy footprint index evidenced the better performance in land sparing of the integrated system as compared to the large-scale crop system. This result is aligned with previous studies that demonstrated that agricultural intensification could help spare areas in the Brazilian agriculture frontier (dos Reis et al., 2020; Garrett et al., 2018; Gil et al., 2018; Macedo et al., 2012). The high livestock productivity in the integrated crop-livestock system is crucial for this positive result.

Moreover, considering the vast livestock area in the Amazon, the potential effect in land sparing in a scenario of widespread adoption of integrated systems in livestock areas could be enormous. Only in Mato Grosso, the livestock area in 2017/18 season was 23 million hectares (IMEA, 2020). In a scenario of integrated system adoption in 25% of pasture areas, maintained all economic results in terms of price and productivity, the potential land sparing for 2017/2018 season would total 1.03 million hectares (dos Reis et al., 2020).

The Brazilian government has been encouraging the adoption of the integrated systems as a public policy to establish sustainable agricultural practices in the Cerrado and Amazon regions as presented in the ABC Plan (Brasil, 2012a), in the National Climate Change Policy (NCCP) (Brasil, 2010), as well as in the Paris Agreement (Brasil, 2016). The carbon-emergy indicator highlighted the integrated system performance in increasing food production and, simultaneously, reducing CO_2 emissions. Taking into account the wide potential area to adopt integrated systems in the Cerrado and Amazon, the contribution of this system to minimize agriculture CO_2 emissions could be immense (Carvalho et al., 2010; Gil et al., 2018; Strassburg et al., 2014).

4.5. Limitations and next steps

This research relies on one year of data. For next steps of this research agenda, efforts should be concentrated in increasing the dataset by building a time series analysis for the three agricultural systems to enhance the understanding about the positive and negative outcomes of each one, and improving data description to identify the extent of renewability for inputs from outside the system's boundary. Furthermore, the economic analysis performed considered only the commercial output of each system. This approach could be enhanced by considering monetary values for the ecosystem services provided by the agroecosystem. Finally, some UEVs used were built for productive conditions different than those evaluated in this paper. Since agriculture is a crucial economic activity in Brazil, and considering the vital relevance of the Cerrado and Amazon biomes to promote sustainability on a global scale, research efforts focusing on enhancing the information base for Brazilian agriculture needs to be implemented.

5. Conclusion

The expansion and intensification of agricultural production to meet growing global demand is exerting rising pressure on the

Earth's carrying capacity, particularly its capacity to absorb waste and GHG emissions (Ayres, 1993; Davis et al., 2012; Foley et al., 2011; Georgescu-Roegen, 1977). Given this limited carrying capacity (Ehrlich, 1989; Foley et al., 2011; Lambin and Meyfroidt, 2011; Steffen et al., 2015), it is increasingly critical to shift agricultural systems toward arrangements that maintain productivity while reducing waste and emissions. This paper sought to evaluate and compare the environmental and economic performances of the primary agricultural systems in the Brazilian Cerrado and Amazon, using economic accounting and the emergy synthesis approach originally proposed by Odum (1996). Our results highlighted the inherent contradiction of analyzing only the economic dimension of agricultural production if we are focused on evaluating how the agriculture sector can contribute to sustainable development.

The emergy indicators set showed that the social cost of large-scale continuous crop system is higher than its social benefits. The crop system is highly profitable, but its high private economic performance relies on a high social cost - an intensive use of external inputs. As a consequence, continuous cropping imposes high stress on the environment, making it unsustainable in the long-run. The extensive beef cattle system is shown to be unsustainable in even more dimensions - low productivity, low profits, and high emissions. In contrast the integrated system achieves high profitability, while dramatically reducing environmental impacts.

Yet, extensive cattle ranching remain the most common land use in the Brazilian Cerrado and Amazon. Though many pasture areas are being replaced by soy (and corn) croplands (Lapola et al., 2014; Macedo et al., 2012), these new cropping areas are mostly continuous systems and the adoption of integrated systems remains limited (Embrapa; Rede ILPF, 2017). Public policies focused on supporting the widespread adoption of integrated systems (i.e ABC Plan and Paris Agreement (Brasil, 2016, 2012a)) could be an effective instrument to promote sustainable development in the Cerrado and Amazon biomes. However, to date their uptake has been lower than expected (Observatorio ABC, 2016). Improvements to the policy's implementation, such as reducing bureaucracy and simplifying credit access, expanding technology transfer programs and improving rural assistance should be implemented to boost adoption of integrated systems and increasing ABC Plan effectiveness. Simultaneously, it is imperative to strengthen anti-deforestation legislation (Brasil, 2012b) as an instrument to reduce pressure to clear forests while incentivizing sustainable intensification of livestock systems (Garrett et al., 2018; Gibbs et al., 2016; Nolte et al., 2017).

More broadly, the results presented here underscore the need to direct greater research focus to assessing the potential of integrated systems to contribute to a reduction of the global food system's environmental footprint. Within the suite of sustainable agriculture innovations available, integrated systems may offer a model that is particularly scalable given its suitability for commercial commodity systems, providing both high productivity and high profitability. The strong performance of these systems in the world's largest agricultural frontier has relevance in and of itself for global sustainable development, but also provides support for its potential uptake in other regions. However, worldwide these systems remain uncommon and encounter significant structural barriers. There are also many remaining knowledge gaps about the social, economic, and environmental feasibility of these systems in different regions (Garrett et al., 2017). Further research is needed to understand whether the results of this study hold across other major global production regions and to support greater adoption of integrated systems should they prove to be as promising as the growing evidence base in Brazil suggests.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124580.

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