PROGRAMA DE PÓS-GRADUAÇÃO
EM DESENVOLVIMENTO SUSTENTÁVEL (PPG-CDS)
UNIVERSIDADE DE BRASÍLIA

TESE DE DOUTORADO

TÍTULO:

INTEGRATED CROP-LIVESTOCK-FOREST SYSTEMS: A BRAZILIAN ALTERNATIVE FOR AGRICULTURE SUSTAINABILITY

Aluno: Júlio César dos Reis
Orientador: Dr. Saulo Rodrigues Pereira Filho - CDS/UnB

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Para a minha mãe, minha esposa e minha filha.

AGRADECIMENTOS:

Concluir uma tese de doutorado no atual momento em que se encontra o Brasil é uma vitória e tanto. A ciência hoje é deixada de lado, atacada em todas as frentes, e as discussões sobre sustentabilidade, e mais especificamente, sobre agricultura sustentável no Cerrado e na Amazônia, apesar de fundamentais, tem sido sistematicamente relegadas à segundo plano. Ademais, estamos diante de uma pandemia, situação totalmente nova para a grande maioria da população, e que tem sido devastadora, muito em decorrência da incapacidade dos nossos governantes em lidar com esse problema e com seus desdobramentos sociais e econômicos.

Ainda assim, a ousadia dessa pesquisa, ao se propor a analisar o potencial econômico, social e ambiental de uma tecnologia brasileira para promoção da agricultura sustentável na principal região agrícola do país, e do mundo, foi recompensada com resultados inovadores, oferecendo contribuições importantes para a elaboração de políticas públicas, e indicando caminhos para melhorarmos o nosso entendimento sobre modelos alternativos para a agricultura de larga escala e para a pecuária extensiva, os modelo típicos de agricultura e pecuária observados nas regiões Cerrado e Amazônia.

A realização dessa pesquisa envolveu a construção de uma ampla rede de pesquisa, e divido com todos os parceiros e amigos os resultados alcançados.

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Integrated Crop-Livestock-Forest systems: a Brazilian alternative for agriculture sustainability

ABSTRACT:

Agricultural intensification can play an essential role in the global challenge of meeting increasing global food demand while conserving and restoring natural ecosystems. The adoption of sustainable agricultural systems in the Brazilian Cerrado and Amazon is globally relevant, on the one hand due to the amount of commodities produced in these regions, and on the other by the critically important ecosystem services provided by these biomes. A Brazilian innovative technology with encompass the features of sustainable agricultural systems are the integrated crop-livestock-forest (ICLF) and the integrated crop-livestock (ICL) systems, which re-couple crop, livestock and forest production at the farm scale, and, therefore, have been considered a promising strategy to increase agricultural sustainability on Cerrado and Amazon regions. However, there are knowledge gaps about the economic, social and environmental potential of integrated systems to be used as an effective strategy to promote sustainable agriculture in the Brazilian agricultural-forest frontier. The main objective of this thesis is to assess the three dimensions of sustainability: economic, social and environmental, in typical agricultural systems located in Mato Grosso, Brazil, the largest grain and beef producer in the country, which spans the ecologically diverse biomes - Amazon, Cerrado and Pantanal -, focusing on information generation, on the farm level, to enhance adoption of integrated systems. First, we presented an economic analysis and compared the economic performance of an integrated crop-livestock system to a continuous crop (soybean/corn) system and a continuous livestock (beef cattle) production system from 2005-2012. In the next chapter, we used the emergy synthesis approach to assess and compare the environmental performance of an ICL system to a continuous crop and a continuous livestock system. Our analysis used survey and empirical case study data from the 2017/18 crop. Economic indicators such as gross revenue, production costs and profitability were calculated to complement the sustainability assessments. Finally, in the chapter four, we applied a fuzzy logic approach to build partial indicators for the economic, environmental, and social dimensions of agricultural performance, further integrated in an overall sustainability index considering actual farm data for the 2018/2019 cropping season. We surveyed 22 farms categorized among the three most representative agricultural production systems used in the Cerrado and Amazon, as follows: i) continuous crop rotation (soybean - corn), ii) continuous livestock, and iii) integrated systems (crop-livestock and livestock-forest). Our results demonstrated that the ILPF systems are economically competitive even in a region highly specialized in large-scale crop production. The emergy analysis highlighted the main contradictions of the large-scale farming system: the social benefits are lesser than the social costs. The traditional livestock system showed low profitability and high negative environmental impacts suggesting that this activity depends on specific public policies to improve its performance. In contrast, the ILPF systems proved to be an efficient alternative to increase livestock production and, simultaneously, reduce GHG emissions as well as the pressure over natural forest. Moreover, the ILPF systems showed greater efficiency in the use of inputs and a balanced performance between economic, social and environmental dimensions. These results provide further support for Brazil’s investment in integrated systems as part of its climate mitigation and sustainable agricultural development plans, and offer quality information to policy makers to support implementation of policies to deal with the environmental impacts of agricultural intensification, while simultaneously increasing food production and socioeconomic development in the Brazilian agricultural forest frontier.

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CHAPTER 1

INTRODUCTION

1- INTRODUCTION

1.1- Research Problem

Transformations in economic, social and environmental structures observed on a global scale over the past years have engendered several challenges for the agricultural sector. One of the most important of such challenges is producing enough food for increasing global demand without causing environmental impacts or degrading the potential for producing food in the long-term (Foley et al., 2011; Godfray et al., 2010; Steffen et al., 2015). This is a particularly challenging issue given agricultural production is expected to double to meet the increase in population which is forecasted to reach 9.8 billion people by 2050 (United Nations, 2017).

Agriculture is currently the most extensive land use activity, accounting for around 38% of the earth surface, uses more water than any other sector, and is the second-largest contributor to climate change, with 24% of the total global GHG emissions (Davis et al., 2012; Foley et al., 2011; IPCC, 2013; Tubiello et al., 2015). However, in Brazil, agriculture is the largest GHG emitting sector representing 33.6% of all Brazilian emission in 2016 (SIRENE, 2017). Effectively addressing this challenge will inevitably require changes in production strategies that could have important economic implications for agricultural producers.

In this context, the Brazilian government has been showing great interest in the research, improvement and dissemination of on farm practices that enhance economic results in agriculture but, simultaneously, contribute to the reduction of the negative social and environmental impacts associated with this activity, notably in Cerrado and the Amazon regions (Brasil, 2013, 2012a).

Afterward the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP-15), in Copenhagen 2009, the Brazilian government indicated the following climate change mitigation actions, included in the National Plan of Climate Change (PNMC) (Brasil, 2010a) : i) the reduction in the Amazon and Cerrado deforestation; ii) the expansion of energy efficiency and; iii) the widespread adoption of additional and sustainable agricultural practices[1] (Brasil, 2012a, 2010a). The potential greenhouse gas (GHG) reduction of this actions ranging from 36.1 to % 38.9 in relation to projected Brazilian emissions by 2020 (Brasil, 2012a).

To encompass the agricultural sector, a specific plan was proposed: the Sectorial Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low Carbon Economy in Agriculture (ABC Plan) (Brasil, 2012a). The agricultural commitments, described in the ABC Plan, refer to actions aimed at: i) the recovery of 15 million hectares of degraded pastures; ii) expansion of the integrated crop-livestock-forest (ICLF) system by 4 million hectares; iii) expansion of the no-tillage system area by 8 million hectares; iv) expansion of biological nitrogen fixation in 5.5 million hectares of cultivated areas, replacing the use of nitrogen fertilizers; v) expansion of forest planting in 3 million hectares and; vi) expansion of the use of technologies to treat 4.4 million m^3 of animal waste (Brasil, 2012a).

Finally, succeeding Brazil's ratification of the Paris Agreement in 2016 (Brasil, 2016), the following targets were set for the agricultural sector's contribution to reducing greenhouse gas (GHG) emissions by 2030: i) strengthening of the ABC Plan as the main strategy for sustainable development in agriculture; ii) the additional restoration of 15 million hectares of degraded pastures by 2030 and; ii) the increase of 5 million hectares of ICLF systems by 2030 (Brasil, 2016).

As a common target in these initiatives to enhance sustainable agriculture systems, especially in view of the significant contribution of this sector to Brazilian CO_2 emissions, responsible for 31.3% of direct emissions for 2015 (SIRENE, 2017), it is the commitment to increase the areas of ICLF, particularly in the Amazon and Cerrado regions. These agricultural systems aim to

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[1] This voluntary commitment was assumed in the Law No. 12,187, of December 29, 2009, which instituted the National Policy on Climate Change (NPCC). Art. 11 of the NPCC states that Federal Government will formulate of sectorial plans for mitigation and adaptation to climate change, to encourage adoption of low carbon economy agenda. These plans must be made in accordance with the NPCC, considering the specificities of each sector, including the Clean Development Mechanism – (CDM) and the Nationally Appropriate Mitigation Actions (NAMAs). The decree No. 9,578, of December 22, 2018, established actions that will be implemented to reduce emission between 1,168 and 1,259 billion tons of CO2

improve the sustainability of agriculture 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; Herrero et al., 2010; Kluthcouski et al., 2003; Lemaire et al., 2014; Macedo, 2009; Nair, 1991). Following the definition used in the ABC Plan as well as in the Paris Agreement and in the National Policy of the Integrated Crop-Livestock- Forest system, and to accomplish the objectives proposed in this research, we consider as ICLF systems all possible combinations of their three components: crop-livestock systems (ICL), crop-forest systems (ICF), livestock-forest systems (ILF) and finally crop-livestock-forest systems (ICLF) (Brasil, 2016, 2013, 2012a).

The integrated systems represent a strategy to intensify resource uses - labor, land, and capital – to increase productivity, diversifying production and sparing land use (Franzluebbers, 2007; Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016). Furthermore, integrated systems can be used to recover degraded pastures areas by using crop residual fertility to restore soil quality and the crop revenue to fund further system improvements (De Oliveira et al., 2013; Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011). Prior studies in Brazil, mainly in Cerrado regions, have also shown that integrated systems can increase production efficiency since they contribute to: i) improvements in soil quality; ii) water conservation; iii) an increase of animal performance; and iv) a reduction in greenhouse gases emissions (Kluthcouski et al., 2003; Macedo, 2009; Oliveira et al., 2018; Salton et al., 2014; Vilela et al., 2011).

The public policies and actions proposed by Brazilian government for promoting sustainable agricultural systems are globally relevant since Brazil is one of the main agricultural players in the global market (FAOSTAT, 2020). Brazil is the world leader in production of sugar cane, coffee and orange juice. Moreover, it is among the main world producers of soybean, bean, corn, cassava and cotton (FAOSTAT, 2020; MAPA, 2020). Considering livestock sector, Brazil has the second largest cattle herd in the world (213.5 million head), it is the third largest producer of chickens and fourth in the production of milk and pork (FAOSTAT, 2020; IBGE, 2020).

This remarkable productive performance combined with both its comparative and competitive advantages for agriculture, and with the potential for intensifying agricultural production provides conditions for Brazil to take a central position in discussions about food security on a global scale for the coming years (Alexandratos and Bruinsma, 2012; Gasques et al., 2010). Furthermore, the international importance of Brazilian agriculture explains its relevance for Brazilian internal economy over the years, (Barros, 2016; Freitas, 2016). Agriculture sector represented 21.4% of the Brazilian Gross Domestic Product (GDP) in 2019, about of R$ 1.55 trillion. The contribution of agriculture was 14.6%, and livestock 6.8% (CEPEA / ESALQ, 2019).

From a strictly economic point of view, the current agricultural model has shown positive results, contributing in an important manner, particularly in recent years, for the Brazilian economic performance (Barros, 2016; Freitas, 2016). However, considering its contribution for the promotion of sustainable development, there are contradictions evidenced: i) by the high participation of the agricultural sector in GHG emissions, ii) by the large areas of degraded pastures, iii) by the negative impacts of the intense use of soil and water resources, and iv) by the increasing social problems in rural areas such as poverty and income inequality (Barros, 2016; Gasques et al., 2010; Gil et al., 2018; Graziano da Silva, 2010; Lapola et al., 2014; Martinelli et al., 2010; Strassburg et al., 2014).

The technological revolution in agriculture based on broad adoption of external inputs such as use of machinery, fertilizers, and pesticides to increase productivity has enormous implications in the energy used and, as consequence, energy disposal by agriculture (Davis et al., 2012; Foley et al., 2011; Odum, 1984). Since every economic process is subject to the Law of Entropy (Georgescu-Roegen, 1986, 1971), agricultural practices such as the use of synthetic inputs tend to increase wastes and energy loss which lead to the degradation of the environment (Ayres, 1993; Foley et al., 2011; Georgescu-Roegen, 1971; Odum, 1996, 1984).

According to the First Law of Thermodynamic, energy entering a system is neither created nor destroyed. The (available) energy is transformed into work: products and services. Moreover, as the Second Law of Thermodynamic demonstrates, every production process is accompanied by energy dispersal. Not all available energy is converted into effective work (Georgescu-Roegen, 1977, 1971; Odum, 1996, 1988). Although energy is conserved in passing through the hierarchical organization of the productive systems, the forms of energy are quite different, and they are not equivalent in the ability to do work. Used (unavailable) energy cannot do any work. It leaves the system in degraded form, in a high entropy stage (Brown and Ulgiati, 2004; Odum, 1996).

The economic mainstream and its mechanistic interpretation of the productive activity expresses the economic system as a close, self-organized and self-sufficient system, only indicating the exchange of services and good produced by firms for salary and workforce provided by families (Georgescu-Roegen, 1973, 1971; Mueller, 2007). This theoretical framework has as fundamental assumption the belief that the economic activity can continue indefinitely. There are no restrictions on production and on accumulation, and the progress can be achieved by technological evolution (Ayres, 1993; Georgescu-Roegen, 1971; Mueller, 2007). It is implicit in this perspective the conception of free substitutability among the factors of production, particularly between natural capital and produced capital, and the belief that market structures are sufficiently efficient to deal with the relative scarcity of a given input via price mechanisms (Ayres, 1993; Daly, 1997; Mueller, 2007, 2005).

On the other hand, from a biological point of view, the economic system is represented as an open system, embedded in the global ecosystem, working similarly then living organisms: taking energy and high quality matter from outside, the environment system, and using it to maintain itself, grow and evolve, and returning them to this external environment in the form of dissipated energy and waste (Georgescu-Roegen, 1986, 1971, 1970). Considering that the economic system works using much more energy than it is provided by the sun (i.e. using fossil fuels), and that the rejects from economic activity are toxic for the vast majority of life on the planet (Ayres, 1993; Ehrlich, 1989; Steffen et al., 2015), the increase in the scale of economic activity may imply the disruption of the biogeochemical cycles that are fundamental to life on earth (Ayres, 1993; Ehrlich, 1989; Mueller, 2007). In this sense, therefore, to produce goods and services, the economic subsystem, inherently, generates restrictions for its continuous reproduction in the long-run (Ayres, 1993; Daly, 1997; Georgescu-Roegen, 1986, 1971).

The relationship between production and environmental degradation depends on the scale of production, the composition of production and the technology adopted in production (Mueller, 2007; Munasinghe, 1999, 1995; Stern et al., 1996). Nonetheless, taking into account the intrinsic transformations into these factors as well as their context-dependency, a key issue to evaluate the economic system impacts on the environment and its sustainability in the long-run is the scale of production (Ehrlich, 1989).

In a general overview, a huge scale of production implies excessive pressure over natural resource. If the consume rate of natural resource by the economic system is higher than its replacement rate, the ultimate result is a reduction on provision of the natural resource (Ehrlich, 1989; Munasinghe, 1995; Steffen et al., 2015). The negative impacts of huge scale of production enlarges considering that there are no plausible technological substitutes for a vital ecosystem service like soil fertility, clean fresh water, clean fresh air, unspoiled landscapes, climatic stability, biological diversity, biological nutrient recycling and environmental waste assimilative capacity (Ayres, 1993; Mueller, 2007). Moreover, this ecosystem service set is outside the market domain, which limits the regulation of its provision or consume via price mechanisms.

Following the perspective that some vital ecosystem services are not replaceable, and the presuppositions of the Georgescu-Roegen’s Fund-Flow model (Georgescu-Roegen, 1970), it is fundamental conserve the services provided by the fund factors of the natural capital to implement a sustainable pattern. The Fund-Flow model gathers the productive factors into two categories: i) funds factors: are the structural elements - “Ricardian land”[2], human capital, and physical capital - which provide services in several processes that occur over time, represented by agents that transform inflows into outflows, are and ii) flows factors: which are inputs or outputs that are either produced or consumed during the operation of a system (Georgescu-Roegen, 1970).

Georgescu-Roegen suggests that each category of capital can be sub-divided in other two, considering the participation of them in the production process. Each capital presents a stock of

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

inputs and a stock of service (Georgescu-Roegen, 1971, 1970). For the natural capital, these two categories are closely interconnected, and even displaying resilience, a huge scale of production, exceeding the capacity of replacement of stock of inputs or the capacity of maintenance of stock of services, can undermine the vital ecosystem services provision from natural capital (Ayres, 1993; Mueller, 2007).

Considering the modern agriculture, besides its great dependence on synthetic inputs which contribute with the rising of the entropy of the global ecosystem, it is crucial highlights that its expansion causes destruction of habitats and biodiversity by converting forest areas into cultivated areas (Altieri, 1999; Benton et al., 2003; Schulz et al., 2019; Steffen et al., 2015). Moreover, for the biogeochemical cycles work to maintain the stability of the global ecosystem, biodiversity is necessary (Ayres, 1993; Mueller, 2007). The importance of the biogeochemical cycles to maintaining the conditions for life - including human life - arises partly from their role in stabilizing temperature, humidity, salinity, acidity (pH) and other climatic conditions, and partly from their ability to convert toxic waste products from one form of life back into nutrients for another form of life (Ayres, 1993; Ehrlich, 1989).

Furthermore, the great nutrient cycles of the natural world such as - carbon, oxygen, nitrogen, sulfur, phosphorus, calcium, potassium, chlorine, iodine – need balanced inflows and outflows and constant stocks in each cycle stage (Ayres, 1993). Since the nutrient cycles are closed, stables and far away from thermodynamic equilibrium, a large enough perturbation could cause an irreversible collapse of the system, representing a threat to global ecosystem and damaging the services provision from natural capital (Ayres, 1993; Ehrlich, 1989; Mueller, 2007).

The main service provided by the environment is its ability to regenerate and absorb the waste and emissions from the economic system (Ayres, 1993; Georgescu-Roegen, 1977, 1971; Odum, 2007). However, since there is insufficient information about the stabilizing mechanisms for the biogeochemical cycles, is it not possible indicates how big an external pressure should be to generate an irreversible trajectory of unsustainability (Ayres, 1993; Ehrlich, 1989; Mueller, 2007). On the other hand, negative impacts on environment related to the huge scale of agriculture such as high GHG emission, deforestation, large degraded pasture areas and the considerable use of fertilizers evidence that this activity already exert great pressure on the environment. Therefore, a strategy to promote sustainability on the agricultural sector should be based on the adoption of productive systems more productive and less dependent of synthetic input.

Also, Georgescu-Roegen’s contribution to the economic theory of production states that matter also exists in two states: available and unavailable, and as well as the energy it degrades continuously and irrevocably from the former to the latter state (Georgescu-Roegen, 1977). In spite of the raising of technological advances in matter recycling, only part of the economic waste is recyclable (Georgescu-Roegen, 1986, 1977). Taking into account that the Earth's absorption capacity is limited (Foley et al., 2011; Lambin and Meyfroidt, 2011; Steffen et al., 2015), the adoption of agriculture systems less dependent on external inputs is a welcome initiative to promote sustainability.

These principles suggest that the conservation of environmental resources, particularly non-renewable ones, is a central condition for sustainable development, considering that technological advancement, although fundamental to improving production, cannot replace vital ecosystem services for the maintenance of living conditions (Ayres, 1993; Daly, 1997; Ehrlich, 1989; Pearce et al., 1996, 1994). Even different capital forms (i.e., economic capital, human capital and natural capital) are not entirely replaceable (Georgescu-Roegen, 1970; Pearce et al., 1996, 1994). Since the economic use of matter and energy to produce goods and services follow an irreversible direction, the energy or matter can be used only once (Georgescu-Roegen, 1986, 1977).

As a result, to improve sustainability of agricultural production, it is necessary to expand the use of farming practices and agricultural systems that reduce the dependence of external inputs and increase their efficiency. Moreover, it is necessary to encourage agricultural systems that increase productivity of available resources, 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 integrated systems, due to their structural characteristics and their potential in terms of economic, social and environmental results, can be placed as an instrument for sustainable agricultural production (Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016; UNEP, 2011; Vilela et al., 2011). In this study, it is considered sustainable those agricultural systems that preserve or enhance the productive capacity of the environmental resources used, reduce biodiversity loss, display positive economic return, generate increasing levels of social welfare (Hansen, 1996; Pretty, 2008; Schaller, 1993) and, simultaneously, do not harm their capacity to continue over time (Foley et al., 2011; Godfray et al., 2010; Hansen, 1996; Herrero et al., 2010; Smit and Smithers, 1993).

The multiplicity of configurations and types of the integrated systems allow adoption of this technology by different kind of producer, regardless size, region, product or any other structural characteristic (Balbino et al., 2011; Macedo, 2009; Vilela et al., 2011). However, adoption of the integrated systems tends to be related to high initial investment, particularly in machinery and herd formation which, in general, limit the adoption by small farmers (Balbino et al., 2011; Cortner et al., 2019; Costa et al., 2012). Another structural limitation is associated with scale of production. To be economically viable, high investments in commodities production needs to be connected with large areas. Therefore, to accomplish the objectives proposed in this research, we consider the integrated systems as alternative to large scale continuous crop systems, such as continuous rotation soybean-corn, and to extensive livestock such as livestock observed in the Amazon region. This perspective is aligned with Brazilian government public policies to encourage ICL and ICLF adoption as strategy to reduce environmental impact of agriculture, specially, the reduction of GHG emission and the pressure over natural vegetation areas in Cerrado and Amazon regions (Brasil, 2016, 2012a, 2010a).

Considering farmer’s perception about the potential benefits of adoption of the integrated systems, crop farmers highlight the possibility to increase economic returns, the reduction of market risk, the agronomic benefits generated by crop rotation, and the reduction of the environmental impacts. On the other hand, cattle ranches indicate the reduction of the environmental impacts as the main result. Still, they consider as relevant benefits the possibility to reclaim degraded pasture and the agronomic benefits generated by crop rotation (Embrapa;

Rede ILPF, 2017; Skorupa and Manzatto, 2019) . However, despite the socio-economic and environmental potential benefits, the area occupied by ICLF systems in Brazil is still relatively small: 11.5 million hectares (Embrapa; Rede ILPF, 2017), about 5% of the total area occupied by agriculture and livestock, notwithstanding the rising of 9.4% per year in the last 5 years (Embrapa; Rede ILPF, 2017). Since 2010, Brazilian government has allocated significant credit amount and specific funding plans to encourage adoption of technologies included in the ABC Plan. Nonetheless, this public policy has not being effective as expected. In the 2016/17 season, R$ 2.9 billion were made available through the ABC Plan, but only 63% were used by the producers. In addition, only 7% (R$ 118.7 million) was allocated to the adoption of ICLF systems (Observatorio ABC, 2017).

Some factors explain this relatively low adoption rate of ICLF systems such as: i) cultural barriers, ii) high initial investment, iii) shortage of qualified labor, iv) lack of information and, v) lack of technical assistance (Cortner et al., 2019; Embrapa; Rede ILPF, 2017). However, one of the most decisive aspects for producers' decision-making is the comparatively lack of information about the economic performance of ICLF systems (Cortner et al., 2019; Embrapa; Rede ILPF, 2017; Reis et al., 2016). Recent studies aimed to identify the economic benefits provided by the integrated systems (Costa et al., 2012; da Silva et al., 2012; De Oliveira et al., 2013; Lazzarotto et al., 2010; Martha Júnior et al., 2011; Muniz et al., 2007; Reis et al., 2017). It is noteworthy in these works the focus on assessing the capacity of integrated systems to minimize market risks due to diversification, and on evaluating the economic viability of these systems in comparison with continuous crop systems and continuous extensive livestock systems.

Moreover, in Brazil, there are incipient studies considering the ICLF systems as a consistent strategy for promoting sustainable development in agriculture (Cortner et al., 2019; Garrett et al., 2017, 2020). The literature about evaluation of the potential benefits of the ICLF systems presents clear bias for focus on different dimensions - economic, social and environmental - in a fragmented way, does not considering the interdependence among the various dimensions that, together, would indicate the potential use of ICLF systems as a sustainable development strategy.

Bearing these issues in mind, this research proposal aims to provide economic, social and environmental information about ICLF systems as well as for continuous agricultural and continuous livestock systems in the state of Mato Grosso, Brazil's main agricultural producer state (CONAB, 2020; IBGE, 2020; MAPA, 2020), with the objective of assisting farmers in their decision-making process regarding the adoption of integrated systems and, as a consequence, contributing with Brazilian government to the achievement of the goals to expand ICLF areas assumed internationally.

Finally, the proposal to use integrated systems as a sustainable alternative for current agriculture is aligned with Brazilian government plans that aims implementing a sustainable land use in Cerrado and the Amazon regions. Among these government plans, we can highlight the Sustainable Regional Development Plan for the Area of Influence of BR-163 (Rodovia Cuiabá-Santarém) (Brasil, 2007), the Xingu Sustainable Regional Development Plan (Brasil, 2010b), and the Sustainable Amazon Plan (PAS) (Brasil, 2008).

1.2- Initial premises

1.2.1- Analysis considering farm level

In this study, we focus on the farm level and relate sustainability with production activities and their social, economic and environmental outcomes (Cornelissen et al., 2001; Gómez-Limón and Sanchez-Fernandez, 2010; Hansen, 1996; Sattler et al., 2010; Schaller, 1993; van der Werf and Petit, 2002). Since we are interested in the results effectively generated by agricultural systems, it is on the farm level that these set of information can be effectively observed. It is on the farm level, specifically on the farmer practices, that inputs can be properly assessed regarding the generation of agricultural sector impacts on global scale, such as climate change and price fluctuation on commodities market. Finally, as highlighted, even demonstrating great potential, it is not clear yet, on the farm level, the performance on the integrated system as an efficient sustainable alternative to large-scale crop systems or extensive livestock.

1.2.2- Why Mato Grosso?

Mato Grosso is the leading crop and livestock producer in Brazil: 28% of soybean, which represents 10% of world soybean production, 33% of corn and 71% of cotton productions are cultivated in Mato Grosso (IMEA, 2020), and spans three ecological biomes: the Amazon, Cerrado, and Pantanal (IBGE, 2020; IMEA, 2020). Furthermore, 15% of Brazilian beef cattle herd, 30.1 million of heads, are bred in Mato Grosso pastures (IBGE, 2020). As counterpart, Mato Grosso is one of the majors responsible for deforestation in the Amazon region. Only in 2019, 1,685 Km^2 of forest was deforested in Mato Grosso (INPE, 2020). Therefore, the adoption of sustainable agricultural systems in this region has implications not only for Brazil, but rather for global society.

1.2.3- Why the Integrated Crop-Livestock-Forest systems are a relevant research issue?

The integrated crop-livestock (ICL) and crop-livestock-forest (ICLF) systems are a Brazilian technology developed in beginning 1990s to boost sustainable intensification on agriculture and to increase the efficiency in productive resource use in agricultural systems in Cerrado and the Amazon regions, particularly, environmental resources (Balbino et al., 2011; Kluthcouski et al., 2003; Macedo, 2009). The initial focus on the integrated systems use was to adapt soil conservative practices, such as no-tillage practices for reducing soil loss and leaching, with strategies to increase soil organic matter and, as consequence, enhancing soil quality and its productivity, particularly in Cerrado regions (Kluthcouski et al., 2003; Salton et al., 2014; Vilela et al., 2011).

One of the most negative impacts of modernization of agriculture, characterized by intense use of machinery and external inputs as pesticides and fertilizers, is soil degradation (Davis et al., 2012; Kluthcouski et al., 2003). The widespread use of agricultural technologies from temperate regions in Brazil, mainly in fragile soils regions such as Cerrado and the Amazon, explains the large degraded areas observed on these biomes (Fearnside, 2005; Kluthcouski et al., 2003; Valentim et al., 2002; Vilela et al., 2011). Since tropical regions displays high temperatures and high precipitation levels, organic matter decomposition process in those areas are faster than observed in the temperate regions. Therefore, if none soil conservative practices are implemented, the ground cover is impaired and the soil remains exposed long periods over year (Kluthcouski et al., 2003; Salton et al., 2014).

Pasture degradation and its implication for both soil fertility decline and GHG emission is a relevant issue that compromises the continuity of agricultural production in Cerrado regions (Strassburg et al., 2014; Valentim, 2016; Vilela et al., 2011). Cerrado displays pasture area of 62.7 million hectares, and 55% of this total (35.1 million hectares) shows some level of degradation (LAPIG, 2018). Among the most important factors related to pasture degradation are the absence of pasture management, which imply reduction of pasture productivity over years, and the inefficient management of animals causing soil compaction, erosion and soil nutrients loss (Gil et al., 2018; Strassburg et al., 2014; zu Ermgassen et al., 2018). The integrated systems are especially useful to deal with these issues once they were developed, initially, to improve pasture performance and reclaim degraded pasture, contributing to sustainable intensification of agriculture in Cerrado and, as consequence, reducing pressure over scarce natural vegetation areas in this biome (Macedo, 2009; Vilela et al., 2011).

The ICL systems are an innovative process which associate no-tillage practices with pasture cultivation to enable ground cover over year reducing soil loss and retaining soil moisture in tropical regions (Balbino et al., 2011; Vilela et al., 2011). To take advantage of Brazilian agricultural aptitude and the possibility of more than one harvest over year, research institutes focused on development of tropical grass to enhance ground cover. A considerable set of grass species, mainly from *Urochloa* (Brachiaria) genus[3], was developed for intercropping with crops such as corn and millet. The synergy between crop and pasture rotation improve soil quality, increase productivity, reduce weed and can be a natural control of pest and disease (Kluthcouski et al., 2003; Macedo, 2009; Vilela et al., 2011). Therefore, this technology became a central strategy to reclaim degraded pasture since cattle ranchers can fund pasture reclaims with crop revenue, and an efficient strategy for crop farmers improve productivity and reduce fertilizers and pesticides usage (Costa et al., 2012; Salton et al., 2014; Vilela et al., 2011).

Furthermore, the increasing social concern about agricultural impacts on climate change, mainly due to its high GHG emission and its negative impact on biodiversity (Benton et al., 2003; Donald and Evans, 2006; Gil et al., 2018; IPCC, 2013), together with the increasing demand for

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[3] The identification of grass genus was standardized following the Germplasm Resources Information Network (GRIN) from USDA. However, it is noteworthy consider that Urochloa genus is the same that Brachiaria genus.

wood have encouraged researchers to introduce forest in this system as a strategy to enhance GHG mitigation from agriculture, to reduce deforestation and reduce biodiversity loss. The extensive use of pesticides and fertilizers and the adoptions of monocropping productive system is widely recognized as a significant threats to biodiversity (Altieri, 1999; Benton et al., 2003; Donald and Evans, 2006). The reintroduction of forest can increase the landscape permeability, improve habitat heterogeneity, intensify species fluxes and reduce predation risk from species witch depend for vegetation complexity as escape tactics (Goulart et al., 2013; Perfecto and Vandermeer, 2010). In sum, the forest component can be used as a strategy to enhance connectivity of agricultural landscape (Donald and Evans, 2006; Goulart et al., 2013; Perfecto and Vandermeer, 2010). However, as the ICLF systems are more complex, requiring high level of organization while forest products present longer production cycle, it is currently observed a predominance of ICL systems (Embrapa; Rede ILPF, 2017).

Lastly, the results observed for ICL and ICLF adoption in Mato Grosso for the 2017/18 season highlight the remarkable potential of this technology. In that season, 1.8 million hectares was allocated for integrated systems while 10.7 million was used for crops and 23 million hectares for pastures (dos Reis et al., 2020; IMEA, 2020). Only in one year, the integrated system adoption spared 400 thousand hectares, mitigating the emission of 3.8 million tonnes CO2eq and producing UDS 2.5 billion, 16% of Balance of Trade of Mato Grosso (dos Reis et al., 2020).

This enormous potential illustrates the relevance assumed by the integrated systems in the Brazilian government sustainable agriculture agenda as a prominent sustainable alternative to large-scale agriculture and for traditional livestock in Cerrado and the Amazon regions (Brasil, 2013, 2012a, 2010a). This technology can be a sustainable alternative for Brazil to consolidate its position as a global leader of food production and as a diffusion center of sustainable agricultural practices. Finally, besides its connection with Brazilian agricultural productive specificities, the ICLF system show huge potential to support Brazilian government to achieve the Sustainable Development Goal (dos Reis et al., 2020; Reis et al., 2016). A representation of ICLF direct contribution of SDG achievement is displayed on table 1.

SDG	Target
2- End hunger, achieve food security and improved nutrition and promote sustainable agriculture	**2.3** - By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.
	2.4 - By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality
8- Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	**8.2** - Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors
	8.4 - Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead
12- Ensure sustainable consumption and production patterns	**12.2-** By 2030, achieve the sustainable management and efficient use of natural resources
15- Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	**15.2-** By 2020, encourage the implementation of sustainable management of all types of forests, stop deforestation, restore degraded forests and substantially increase reforestation globally
	15.3- By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, droughts and floods, and strive to achieve a neutral world in terms of soil degradation

Source: United Nation, Department of Economic and Social Affairs, Sustainable Development

Table 1.1: Integrated Crop Livestock Forest System and Sustainable Development Goals

1.3- General objective

This research aims to assess the three dimensions of sustainability: economic, social and environmental, in typical agricultural systems located in Mato Grosso, Brazil, focusing on information generation, on the farm level, to enhance adoption of integrated systems in the Amazon and Cerrado regions.

1.4- Research questions

i. Are the integrated systems economically competitive in relation to large-scale crop systems, even in regions highly specialized as Mid-North region of Mato Grosso?
ii. Are the integrated systems less dependent from external inputs, more efficient in resource use and more productive than large-scale crop systems?
iii. Are the integrated systems a sustainable alternative to increase beef production and, simultaneously, reduce GHG emission from livestock in Cerrado and Amazon regions?
iv. The integrated systems are an effective alternative to promote sustainable agriculture system in the Amazon and Cerrado regions?

1.5- Thesis outline and chapter's connections

To accomplish the objective and answer the research questions, this thesis was divided into four chapters besides this introduction. The chapter two presents an economic-viability analysis of three agricultural systems located in the Mid-North and North region of Mato Grosso. Besides to provide a comprehensive economic analysis of agricultural systems, this chapter illustrates a useful framework to evaluate and to compare different productive systems. This framework, based on projects economic analysis can be a suitable tool for banks, research institutions and fostering agencies to evaluate economic competitiveness of the integrated systems.

Chapter three displays an environmental analysis, based on emergy synthesis proposed by Odum (1996) of an integrated system in comparison with typical continuous crop and typical continuous livestock. The emergy synthesis approach is a useful framework to evaluate agriculture since this sector relies on the interconnection between environmental and economic subsystems. Therefore, both subsystems contributions need to be accounted to compare resources use and to assess productivity efficiency. In this sense, chapter three complements the economic analysis provided in chapter two and highlights the relevance for considering environmental dimension for evaluating productive activities.

Chapter four shows a comprehensive sustainability analysis using the Fuzzy Set approach (Zadeh, 1965) to build economic, social and environmental indicators for 22 farms in Mato Grosso. The fuzzy approach is a suitable tool to deal with research problems in which the absence of sharply defined criteria generates ambiguous perceptions. The sustainability concept, spite of being a global consensual objective, is intrinsically subjective and implies values judgment usually formulated in linguistic variables which are inherently Fuzzy sets. This chapter provides an innovative and comprehensive indicators set to assess sustainability of agricultural systems, encompassing the economic and environmental analysis presented in chapters two and three. The indicator set comprises 18 variables - 6 for each dimension: social, economic and environmental - and the list were chosen to evaluate the impacts of the scale of agriculture in Mato Grosso on the main dimensions of the sustainable development. A valuable contribution of this analysis is highlights, based on the results of indicators, how the current scale of production of agriculture in Mato Grosso has been generating conditions for its continuity in the long-run.

Lastly, a final chapter summarizes the previous results and highlights the research contributions of this work to evaluate adoption of the integrated systems in Cerrado and the Amazon regions and, as a consequence, supporting Brazilian government commitments to implement a sustainable land use in these regions as a strategy to reduce the agricultural negative impacts on climate change.

CHAPTER 2

ASSESSING THE ECONOMIC VIABILITY OF INTEGRATED CROP-LIVESTOCK SYSTEMS IN MATO GROSSO, BRAZIL

2- ASSESSING THE ECONOMIC VIABILITY OF INTEGRATED CROP-LIVESTOCK SYSTEMS IN MATO GROSSO, BRAZIL

2.1- Introduction

Agriculture is the main economic activity in many low to moderate income countries (FAOSTAT, 2020; World Bank, 2017) and employs a large number of workers worldwide (ECLAC, 2017; FAOSTAT, 2020; UNEP, 2011). In Brazil, crop and livestock production contributes substantially to economic growth – roughly 23% of the Gross Domestic Product (GDP) as of 2016 (USD 336.9 billion) (MAPA, 2017). However, it has also been associated with high levels of greenhouse gas emissions (GEEs) and environmental degradation (Graziano da Silva, 2010; MAPA, 2017; Vilela et al., 2011), as well as increasing income inequality in rural areas (Abramovay, 2000; Balsan, 2006; Graziano da Silva and Campanhola, 2004). Beef cattle production, in particular, has been associated with very low incomes and high levels of land degradation, abandonment, and deforestation (Fearnside, 2005; R. Garrett et al., 2017; Margulis, 2004). In this context, there has been a growing impetus to develop alternative agricultural models that achieve higher productivity and incomes, while reducing environmental impacts, most notably deforestation and greenhouse gas emissions (Graziano da Silva, 2010; Lemaire et al., 2014; Nair, 1991; Porfirio-Da-Silva, 2007; Reis et al., 2016). Improving the sustainability of agriculture in Brazil is a key component of the country's plan to achieve their emissions reduction targets.

Considering this challenge, two agricultural models that have been encouraged by the Brazilian government, mainly in the Amazon and Cerrado region, are integrated crop-livestock systems (iCL) and integrated crop-livestock-forestry systems (iCLF)[4] (Brasil, 2012a). These types of production systems aim to improve the sustainability of agriculture production 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).

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[4] In this paper we will concentrate our analysis in integrated crop and livestock systems because this is the integrated system most adopted in Brazil, mainly in Brazilian Cerrado and the Amazon region.

Integrated systems represent a strategy to intensify resource uses - labor, land and capital, to increase productivity, while also diversifying production and sparing land for conservation or other uses (Franzluebbers, 2007; Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016). Production diversification has the additional benefit of reducing market risk, since farmers have opportunities to manage their product portfolio to take advantage of agricultural market price fluctuations (Herrero et al., 2010; Lazzarotto et al., 2010).

A key feature of integrated systems, mainly iCL, is that they can be used to recover degraded pastures (Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011) by using residual fertility from the crop rotation to restore soil quality and finance further system improvements (Costa et al., 2012; Vilela et al., 2011). Prior studies in Brazil, especially in the Cerrado, have also shown that iCL systems can increase production efficiency since they contribute to: i) improvements in soil quality; ii) water conservation; iii) an increase of animal performance; and iv) a reduction in greenhouse gases emissions per unit of food produced (Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011). What is less understood is how economically viable these productions systems are in the Legal Amazon region of Brazil, particularly in light of their potentially high initial investment costs (Gil et al., 2018) and (Appendix 1). This lack of generalized information about the economic performance of iCL in the country’s largest cattle and crop production region may help explain its low adoption rates, despite fairly high levels of government support (De Oliveira et al., 2013; Martha Júnior et al., 2011; Reis et al., 2016; Salton et al., 2014; Vilela et al., 2011).

The aim of this paper is to conduct a comprehensive economic viability analysis of iCL versus a “typical” (as defined below) continuous crop or livestock farm in the Brazilian Legal Amazon state of Mato Grosso, which is the country’s largest producer of soybean and cattle. The evaluation process focuses on assessing the return on investment of these systems to inform both producers’ decision making processes as well as bank financial evaluations for funding iCL projects. The integrated system evaluated in this study pertains to soybeans double cropped with corn, followed by pasture and beef cattle grazing, which is the most common integrated system in the Brazilian Amazon and Cerrado (Balbino et al., 2011; Lemaire et al., 2014; Macedo, 2009; Nair, 1991). Our analysis relies on experimental data for a period of 7 years: 2005 - 2012. In addition to conducting a specific assessment of the case of Mato Grosso, the methods used here can inform future efforts to evaluate the economic viability and returns of iCL at broader scales.

2.2- Material and methods

2.2.1- Case selection

Our analysis focuses on two representative crop and livestock regions in the state of Mato Grosso, Brazil, one of the largest agricultural frontiers in the world (IBGE, 2017; IMEA, 2017; MAPA, 2017). Pastures occupy a majority of the area, followed by soybeans, which are often followed by corn during the course of a single year. Our livestock data were acquired from the municipality of Alta Floresta, in the North region of the state (Figure 2.2), which had the fifth largest cattle herd of the state (706,500 animals) in 2016. Our cropping data were acquired from the municipality of Santa Carmem, in the Mid-North region of the state (Figure 2.1), where about 40% of the soy production occurred in 2016.

The great concentration of agricultural production in the focal livestock and crop regions makes these cases globally important. Yet, they may not be generalizable to all regions within the state, which contains a great deal of climate, soil, and institutional variability. The state spans three ecological biomes: the Amazon, Cerrado, and Pantanal. Since colonization of the region did not begin in earnest until 1960, it is still a highly dynamic environment characterized by agricultural systems across a range of farm sizes and technology levels.

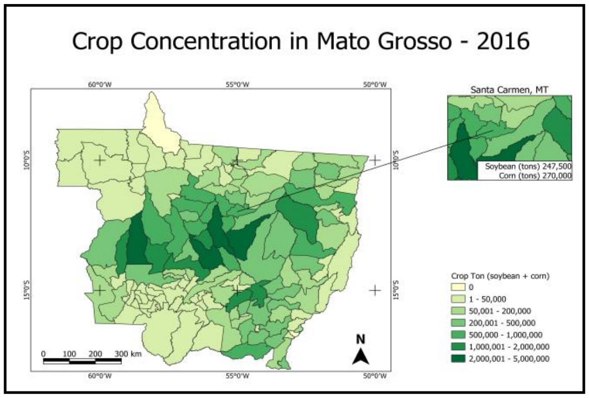

Figure 2.1: Crop concentration in Mato Grosso, 2016

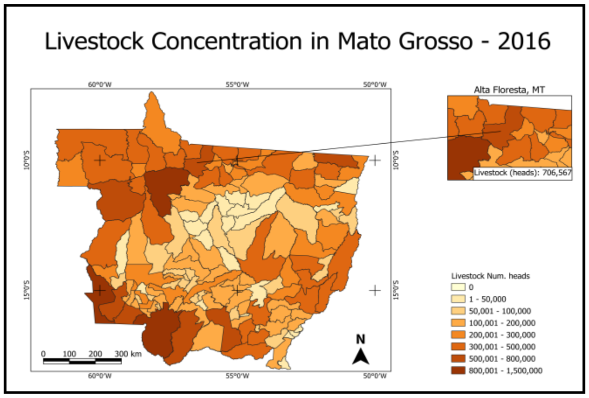

Figure 2.2: Livestock concentration in Mato Grosso, 2016

2.2.2- Defining a "typical" crop or livestock farm in Mato Grosso

We defined the "typical" crop and livestock systems for the North and Mid-North regions of Mato Grosso for the year 2005[5] using farm observations, meetings with local agricultural experts, including farmers, retailers, technicians, consultants, trading managers, and data from the Mato Grosso Institute of Agricultural Economics (IMEA). IMEA carries out a comprehensive yearly economic survey focusing on the main agricultural commodities in Mato Grosso: soybean, corn, cotton, and beef cattle. These surveys are performed in all Mato Grosso regions using focus group meetings that include farmers and representatives from agricultural organizations and businesses. The purpose of these meetings is to gather up-to-date information about costs, revenue, productivity, investments, farm size, management practices, labor, and infrastructure for each commodity across farms in the state.

Based on these data we determined that the typical farm size in Mato Grosso is 700 hectares of cultivated land area. The typical crop farm is defined by an intensive and specialized production system with two crop seasons per year: soybean (*Glycine max*) (October - February) and corn (*Zea mays*) (February - June/July). The initial investment required for the operation of this continuous soybean/corn system was USD 765.63[6] per hectare, excluding the land acquisition cost[7]. This farm possesses a high level of technology in all production stages with high investment in infrastructure and inputs. As a consequence, it has high soybean productivity levels (av. 3.12 MT/ha), as well as high production costs (av. USD 530.45 ha) (Table 2.1). Most soybean production in the region is exported through multinational traders. As of 2005, corn area in the state was still limited, but most production is marketed through domestic channels.

In contrast, the typical livestock farm is characterized by traditional cattle ranches with a low level of technology, low productivity and large areas. Farmers do not invest in sophisticated infrastructure, only basic equipment, such as a corral, troughs and fences. Also, farmers do not

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[5] This year was selected to allow comparison of economic results given that the integrated system experiment started at 2005.

[6] 2005 prices. Conversion using exchange data from official Brazilian Govern database provided by Research Institute of Economic Applied (IPEA): http://www.ipeadata.gov.br/Default.aspx.

[7] The perspective of the analysis was to evaluate the productive activity performed in the area.

invest in pasture management. As consequence, in the dry season, they have difficulties providing adequate nutrition to their herd. The most common cattle breed is Zebu cattle (*Bos taurus indicus*) and pasture is *Urochloa brizantha* cv. Marandu. In contrast to soybeans, the cattle are mainly sold for internal markets and this activity is less responsive of international prices and exchange rates. The initial investment required for the operation of a continuous traditional livestock system was USD 173.73 per hectare, excluding the land acquisition cost.

Integrated crop and livestock systems are still somewhat rare in the study region, so it was not possible to use observations and expert knowledge to characterize these systems. Instead, we draw our data from the first iCL experiment established by the Brazilian Agricultural Research Corporation (Embrapa) on a farm called Dona Isabina in the municipality of Santa Carmen in 2005. The farm has 2,000 hectares cultivated with soybean, corn, and rice (*Oryza sativa*) in rotation and crop sequences. However, the iCL experiment occurred on just 100 hectares of the site. The soils in the test site are yellow Oxisols and the topography is flat, with very little slope. The average altitude is 386m, average annual rainfall of 2,064 mm with a dry season from June to September and average temperatures of 27.6 ºC. To establish pasture rotations and crop sequences, the area of 100 hectares was divided into five parcels of 20 hectares, bounded by fences. The area in which the experiment was implemented had already been cultivated with soybeans in the summer and pearl millet (*Pennisetum glaucum*) as a cover crop after the soybean harvest. Scaling this area up to 700 hectares (to match the size of typical crop and livestock farms in the region) we calculated an initial investment of USD 863.38 per hectare, excluding land acquisition costs.

Each parcel was cultivated with pastures (*Urochloa brizantha* cv. Marandu and *Urochloa brizantha* cv. BRS Piata). The land use of the iCL system followed an annual rotation of crops: soybean or rice in the summer (October - February) and corn or beans (*Phaseolus vulgaris*) immediately following (February - June). The second crop was intercropped with grass pastures. After the second crop harvest, the cattle were allowed to graze on the pastures that remained, which provided them with additional nutrition during the dry season (June to September) when there is low forage availability.

In the first five years of the experiment the herd was a mixture of male and female Zebu cattle acquired in the region. These animals were sold for slaughter when they reached weight of 480 kg. In the last two years, only males were raised, but still slaughtered when they reached 480 kg. The only supplementation used all year long was mineral salt with an average consumption of 90 gr/day during the rainy season and 120 gr/day during the dry season. In the dry season, the cattle also received sorghum silage (*Sorghum bicolor*), soybean residues, corn, and rice produced in the farm processing unit. In all modules mangers for supplementation and watering were available.

2.2.3 - Economic indicators

We used an economic viability analysis approach to compare the economic results of the three agricultural systems (Buarque, 1984; Gitman and Zutter, 2014). This method is established in the economic literature as an instrument to evaluate the economic potential of any investment decision (Buarque, 1984; Lapponi, 2013; Gitman and Zutter, 2014). We used data from IMEA to generate typical crop and livestock farm and survey data to generate the iCL farm. Taking into account the lack of available economic performance data for agriculture systems, the use of IMEA and experimental data are the only feasible approaches for establishing a time series data required to carry out the economic viability analysis presented. The results can be useful for farmers, helping them compare different investment options, as well as for funding agents since they can evaluate different complex agriculture systems using comparable indicators. Since prior studies have identified that a lack of technical information on the economic performance of iCL for both farmers and financers is a key constraint for farmer adoption (De Oliveira et al., 2013; Martha Júnior et al., 2011; Reis et al., 2016; Salton et al., 2014; Vilela et al., 2011; Cortner et al., 2019), our approach may help enable wider scale adoption of this technology. The financial accounting approach used here, which is based on observed outcomes, is also a useful complement to process models, which predict outcomes based on inputs (e.g. Gil et al., 2018 for the same region)

We used the following five indicators to assess economic viability and potential economic returns of the iCL system, continuous soy/corn system, and continuous beef cattle system over 7 years (2005-2012): i) Internal Rate of Return (IRR), ii) Net Present Value (NPV), iii) Return on Investment (ROI), iv) Profitability Index (PI) and v) Payback (Gitman and Zutter, 2014)[8].

Cash flow: To calculate each of these five indicators we first needed to estimate the real cash flow (CF) based on 2005 prices. Following (Lapponi, 2013):

$$CF_t = FCO_t + \Delta I + \Delta CG_t \qquad (1)$$

In which:
FCO_t = Operating cash flow;
ΔI = Net investment in assets;
ΔCG_t = Net investment in working capital.

Apart from the relationship between costs and revenues, cash flow results take into account interest deductions, taxes, and labor charges to demonstrate the cash generation potential of each system[9]. As a measure of yearly profitability, we used the Net Operating Profit After Income Tax (NOPAT)[10]. It represents the net profit that the system generates to remunerate both the funding entity and the producer (Assaf Neto, 2011; Gitman and Zutter, 2014; Lapponi, 2013). As inflation indicator, we used the Broad Consumer Price Index (IPCA) provided by the Brazilian Institute of Geography and Statistics (IBGE), which is the official inflation index in Brazil.

Investment value: Except for the land value, which was not incorporated into the cash flow, all other infrastructure elements required for production activities were considered as if they had been purchased in the initial year of all production systems, 2005. A market survey was conducted with consultants and equipment retailers to collect prices data in the Mid-North region

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[8] Annual results from indicators NPV (Annual Net Present Value- NPVA) and ROI (Annual Return of Investment - ROIA) were calculated and displayed to become easier the comparison between the three systems.

[9] The share of working capital was disregarded and the assets' flow was incorporated into the operating result observed in the last year of assessment.

[10] For construction of the NOPAT, see the supplementary material

in 2005, taking into account the infrastructure needed to set up each farm system.

Discount rate: The discount rate defines the present value of future returns (Buarque, 1984; Gitman and Zutter, 2014). Choosing a discount rate is one of the most controversial points in economic investment analysis because the choice of incorrect values can lead to suboptimal results and decisions (Buarque, 1984; Lapponi, 2013). The project economic evaluation literature defines the discount rate as the opportunity cost of investment, which means that it should reflect the expected return value for alternative available investments with similar risk to the activity being analyzed (Buarque, 1984; Gitman and Zutter, 2014; Lapponi, 2013). This approach, although it incorporates correctly the perspective of the discount rate to be used, is limited by the lack of investment alternatives that can serve as a reference (Buarque, 1984).

As a result, the official savings rate is more commonly used in many agricultural investment evaluations, since it represents a low-risk and low return alternative investment option (Buarque, 1984; Gitman and Zutter, 2014). In other cases, the economy basic interest rate or long-term interest rates has been used, also indicating low-risk investment alternatives, but with higher returns. An important issue regarding the use of these rates as a reference is no consideration of the investor's profile for defining the interest rate to be used.

Given these drawbacks, our study uses the Weighted Average Cost of Capital (WACC), to adjust the variables that make up the investment opportunity cost based on the agent's profile, as well as the level of risk associated with the business being evaluated[11]. The WACC is more appropriate for this evaluation since it considers an agent's decision about which percentage of investment will be funding as well as incorporates market risks of alternative investments (Buarque, 1984; Gitman and Zutter, 2014; Lapponi, 2013). The WACC rate was built taking into account the financial market conditions in Mid-North region in 2005.

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[11] For construction of the WACC, see the supplementary material.

2.2.4 – Incorporating changing land use and market dynamics

Since our study analyzed the economic viability of the three systems over a 7-year period it was necessary to incorporate changes in land use and markets that were occurring over that period. These dynamics include the growing importance of corn as a second crop[12] (resulting in an increase in the on-farm area allocated to integrated crop - livestock systems), changes in the marketing arrangements used by farmers, and a dynamic macroeconomic environment in which real prices for soybean, corn, and beef were changing frequently due to growth in demand and exchange rate variations.

Data from IMEA show that corn as a second harvest crop grew by 14.87% per year in the period 2008 to 2012. To simulate dynamics of land use in the integrated crop-livestock farm, the growth of corn second harvest area in the typical continuous crop farm was used to define the growth of the integrated system area[13] (Balbino et al., 2011; Kluthcouski et al., 2003; Macedo, 2009; Vilela et al., 2011).

Interviews with farmers and specialized consultants who worked in the North and Mid-North regions in 2005 identified that the most common soybean marketing practices used during that time were to sell their harvest over three periods: i) 25% of production was sold in advance, from August to October, ii) 50% of production was sold from November to April, during the harvesting and immediate post-harvest period and iii) 25% of production was sold from May to July, the period of preparation for another harvest. To adjust the revenue dynamics to the trading practices of that period, the crop sales process was adjusted according to the moment of the soybean harvest[14]. Soy sale prices for each period are calculated as the average of the prices observed during the months of soy trading. Similarly, corn sale prices are calculated as the

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[12] According to IMEA, for the 2007/2008 crop year the corn area in Mato Grosso was 1,670,800 hectares and 796,500 hectares for Mid North region. In the 2009/2010 this area increasing to 1,948,020 hectares in the state and 964,000 hectares for Mid North region. The crop year with a more expressive planted area was the 2012/2013, in which were planted 3,702,053 hectares in the state with 1,830,318 hectares in the Mid North region.

[13] The most common practice is to plant corn intercropping with pasture to recover soil quality and provide food for cattle during the driest period of the year in the region, from June to September.

[14] Only the soybeans trading process was taken into consideration, once the corn, at that moment, did not present the economic relevance observed currently.

average of the prices observed from September to November, the main months for corn trading.

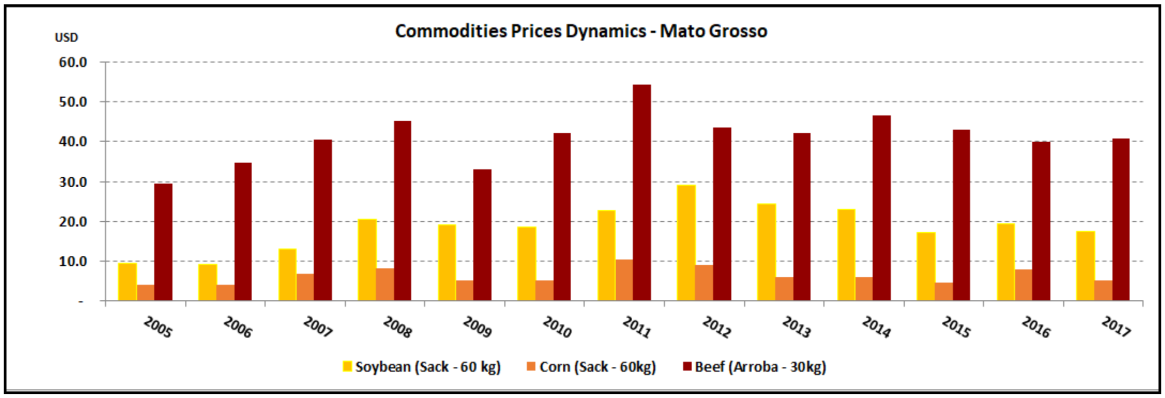

Figure 2.3: Average commodity prices in Mato Grosso from 2005 – 2017

Of particular importance, soybean prices were very low in 2005 and 2006, while production costs remained high (CEPEA, 2007). However, after 2007 the soybean price steadily increased, a trajectory influenced by China's consolidation as the main Brazilian soybean importer (Figure 2.3). In 2012, the soybean price in the Mid-North of Mato Grosso - USD 28.94 per sack (60kg), was three times higher than the value observed in 2005 - USD 9.55 per sack; (IMEA, 2016). Nonetheless, in 2009, the financial crisis complicated production and trading. The devaluation of the Brazilian currency during this period (9% in one year), led to increased crop production costs (10% in 2009), largely as a result of fertilizer imports, while soybean prices remained low (IMEA, 2017).

In contrast, corn prices increased during 2010-2012 as consequence of financial crisis of 2009, since corn production is oriented toward domestic consumption and is not as influenced by global commodity markets. The same domestic market orientation and price dynamics can be seen in the prices for beef, which achieved a historic high price in 2011, USD 54.40 (30kg of live weight). However, a considerable portion of Mato Grosso's beef production is exported, 22.1% on average in the last 5 years (MAPA, 2017), destined mainly for EU, Russia, China and Middle East (IMEA, 2020; MAPA, 2017).

2.3- Results

2.3.1- Productivity

The average cattle productivity in the iCL farm (331.71 kg/ha) was 5 times higher than the typical livestock farm (63.3 kg/ha) (IMEA, 2017) due to the availability of higher quality pasture during the dry period of the year. The productivity of soybean in the iCL farm was also on average 16% higher than crop typical farm during the whole study period (Table 2.1). On the other hand, the input cost of iCL system was 62% lower than the continuous crop farm. Taking into account the high contribution of fertilizers to input costs, this association between higher productivity and lower input cost is likely related to the positive influence of the integrated systems on soil nutrient availability (Carvalho et al., 2010; R. D. Garrett et al., 2017). Further systematic measurement of soil nutrient availability is needed to confirm this hypothesis. A different result was observed with corn. Since corn had little economic importance at that time that the iCL experiment was started at the Dona Isabina farm and the main objective was to provide agronomical benefits for pasture, low productivity corn seeds were used. Moreover, in 2009 and 2010 there was an intense dry period at the crop germination stage which affected productivity.

	Soybean Productivity (Tonnes/hectare)						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	3.58	3.72	3.34	3.63	3.70	3.77	3.56
Crop typical Farm	3.14	3.14	3.14	3.03	3.07	3.33	3.01
	Operational Cost (Inputs, work force and machinery) USD/hectare						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	274.94	149.77	194.26	408.10	233.59	271.58	282.71
Crop typical Farm	375.19	432.65	520.91	631.64	440.84	532.49	779.46
	Inputs Cost USD/hectare						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	165.19	98.83	128.53	280.70	157.49	172.76	180.62
Crop typical Farm	319.29	368.18	443.29	537.52	340.94	435.80	704.73
	Corn Productivity (Tonnes/hectare)						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical	2.19	5.04	4.08	2.82	-	1.95	4.80

Farm							
Crop typical Farm	4.63	4.63	4.63	5.07	4.00	3.99	6.22
	Operational Cost (Inputs, work force and machinery) USD/hectare						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	26.19	57.56	61.82	69.06	64.61	61.52	109.52
Crop typical Farm	225.10	259.57	312.52	378.96	309.30	408.05	459.87
	Inputs Cost USD/hectare						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	16.30	37.63	39.28	48.79	47.21	50.96	79.88
Crop typical Farm	183.43	211.52	254.67	308.80	246.29	338.25	400.28
Cattle Productivity (Kg/hectare) - Kg produced							
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	162.00	372.00	360.00	216.00	402.00	399.00	411.00
Livestock typical Farm	324.00	-	-	-	-	336.00	-
	Operational Cost (Inputs, work force and machinery) USD/hectare						
	2005/2006	**2006/2007**	**2007/2008**	**2008/2009**	**2009/2010**	**2010/2011**	**2011/2012**
iCL typical Farm	897.01	1181.71	1376.48	1003.18	2353.35	2495.65	3679.37
Livestock typical Farm	92.39	108.68	127.78	142.87	138.07	164.78	182.24

Table 2.1: Productivity, operating and inputs cost for a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato Grosso from 2005-2012

2.3.2- Cash flows[15]

The iCL system had the largest investment costs (negative cash flow in years one and two), but also had the largest positive cash flows throughout the remainder of the study period, achieving a positive result of USD 654.04/ha in 2012 compared to USD 460.85/ha for continuous cropping and UDS 27.59/ha for continuous livestock (Figure 2.4). Macroeconomic fluctuations explain most of the changes in cash flows over the study period. In particular, soybean and beef prices increased during the study period (Figure 2.3).

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[15] For a detailed cash flow description, see supplement material

During June to September most continuous livestock farms have to sell off part of their herd, since they do not have conditions to feed them (Gil et al., 2018; IMEA, 2016; Reis et al., 2019; Valentim, 2016), which is thought to cause declines in the local cattle price. The higher pasture productivity obtained in the iCL system on the Dona Isabina farm, translated to higher cattle productivity (331.71 kg/ha annual average) (Table 2.1), and enabled this farm to keep their animals during the annual dry season. Indeed, the pasture management strategy implemented at Dona Isabina provided an annual increase of 14% in cattle productivity over the seven years. Moreover, in 2012, the annual cattle productivity was 2.5 times higher than its cattle productivity in 2005 (Table 2.1). The seasonal dilemma of traditional cattle ranches also enabled the Dona Isabina farm to acquire animals at a low price during the dry season and sell them in periods when prices were high. The seasonal advantage and the high cattle productivity largely explain the better economic results of iCL versus continuous cattle (Figure 2.4).

The iCL farm also resulted in higher cash flows than the continuous crop farm (Figure 2.4), due to the combination of higher productivity and, on average, 62% lower production costs and 51% lower operating costs (Table 2.1). The large reduction in production costs can be attributed to lower fertilizer needs due to improved soil fertility from both manure and nitrogen fixing legumes in the pasture.

The economic fragility of traditional livestock is evidenced by the smaller cash flow throughout the study period (on average USD 23,131.62 versus USD 109,164.24 for continuous cropping and USD 204,318.97 for the integrated system).

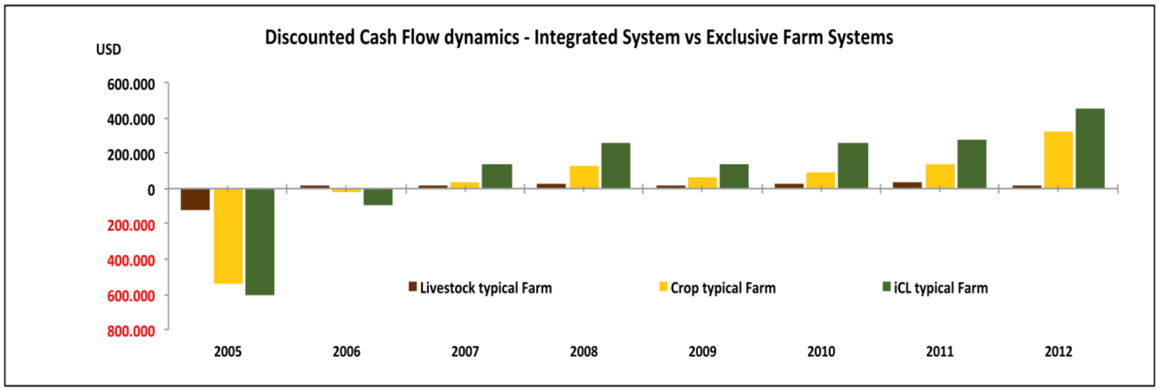

Figure 2.4: Discounted Cash Flow of a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato Grosso from 2005-2012

The iCL farm also outperforms the continuous cropping and continuous livestock systems in terms of the Net Operating Profit After Income Tax (Figure 2.5). This indicator, which can be interpreted as the annual system capacity to provide economic return after taxes and financial expenses (e.g. interest on debt), indicated that the iCL farm provided a greater money supply than the continuous crop and livestock systems throughout the study period, aside from the initial year.

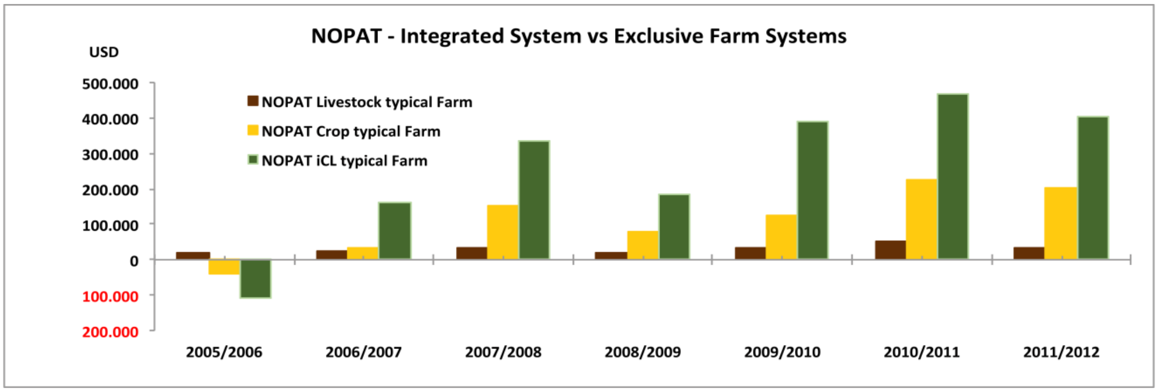

Figure 2.5: NOPAT of a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato Grosso from 2005-2012

Another economic indicator widely used in the project analysis approach is the recovery period of the investment (the number of years of positive cash flows it takes to repay the initial investment and negative cash flows), known in the literature as the payback period. The iCL farm recovered the investment after 4 years (Figure 2.6) while the continuous crop did not recover their investment until year 6. The livestock system recovered the investment after 5 years. In the end of seventh year, the continuous crop and livestock farms had an accumulated cash flow of USD 228,207.46 and USD 40,313.76, respectively. However, the iCL farm had accumulated USD 825,868.81.

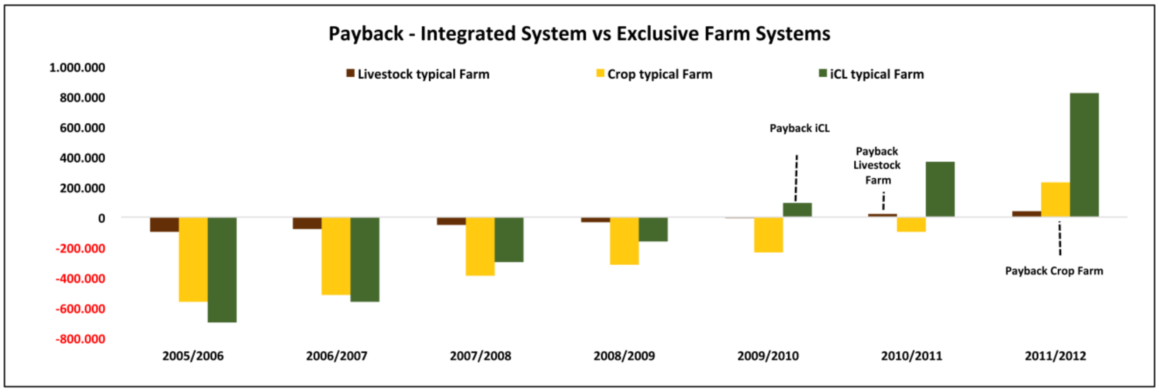

Figure 2.6: Payback of a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato

Grosso from 2005-2012.

2.3.3- Economic viability indicators

The cash flow of all systems provides useful information to elaborate the set of economic viability indicators displayed in Table 2.2. Across all indicators (net present value, internal rate of return, payback, profitability index, and return on investment) the iCL system performs substantially better than the continuous crop and livestock farms. The exception is the higher upfront investment cost per hectare. The livestock farm has the worst performance across all indicators.

Indicators	**Crop typical Farm**	**Livestock typical Farm**	**iCL typical Farm**
WACC	9.66 %	9.18%	9.53%
Investment (USD)/hectare	765.63	173.73	863.38
NPV (USD)/hectare	66.73	5.22	674.17
NPVA (USD)/hectare	13.56	1.04	136.25
IRR	11.32%	10.01%	22.16%
ROI	10.98%	9.64%	18.94%
ROIA	1.2%	0.42%	8.58%
Profitability Index	1.09	1.03	1.78

Table 2.2: Economic viability indicators for a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato Grosso from 2005-2012

3.4 Scenario Analysis

3.4.1 Different Interest rates

All the results presented above are quite sensitive to the discount rate. Here we used the Center-West Constitutional Fund rate, 8.75%, to construct the WACC, as well as the entire set of economic viability indicators because in 2005 there was no specific government loan program to encourage iCL in Brazil. However, in 2010, Brazilian Government implemented the Low Carbon Agriculture Plan (ABC Plan) with incentives and low interest rates for more sustainable agricultural systems, including iCL. The ABC Plan offered interest rates of 5.5% in 2010 (Brasil, 2012a). However, the performance of iCL relative to the other systems does not change if we use the ABC Plan rate or the basic interest rate of Brazilian economy (SELIC) in 2005 (19.24%), a rate used to evaluated investments in stock market (Table 2.3).

Indicators	Crop typical Farm		Livestock typical Farm		iCL typical Farm	
	SELIC (19.24%)	ABC Plan (5.5%)	SELIC (19.24%)	ABC Plan (5.5%)	SELIC (19.24%)	ABC Plan (5.5%)
WACC	13.86%	8.36%	19.24%	5.5%	13.73%	8.24%
Investment (USD)/hectare	765.63	765.63	173.73	173.73	863.38	863.38
NPV (USD)/hectare	(89.98)	124.33	(45.18)	31.52	393.73	776.62
NPVA (USD)/hectare	(20.89)	24.17	(12.27)	5.55	91.07	150.38
IRR	11.31%	11.31%	10.01%	10.01%	22.15%	22.15%
ROI	11.84%	10.71%	14.22%	8.04%	19.99%	18.61%
ROIA	-1.77%	2.17%	-4.21%	2.41%	5.50%	9.58%
Profitability Index	0.88	1.16	0.74	1.18	1.45	1.89

Table 2.3: Simulation with different interest rates - Economic viability indicators for a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato Grosso from 2005-2012

2.3.4- Different Prices

Between 2005-2006, soybean prices were very low in the global market (Figure 2.3). Both soybean and corn prices peaked in 2010 and then again in 2016. To capture the effects of these higher prices we used the average soybean and corn prices observed in the Mid-North region between 2013-2017. For consistency, the cattle prices were also adjusted to the average prices in the Mid-North region between 2013-2017. Moreover, the corn planted area was increased, to match the growth in the average farm-level planted area in the Mid-North in the last 10 years (2007-2017: 46.44%). All other conditions were kept unchanged. As a result of these scenario adjustments, the continuous crop system overtook iCL as a better investment (Table 2.4).

Indicators	Crop typical Farm	iCL typical Farm
WACC	9.66%	9.53%
Investment (USD)/hectare	765.63	863.38
NPV (USD)/hectare	761.38	52.70
NPVA (USD)/hectare	154.66	10.66
IRR	30.54%	10.86%
ROI	21.01%	10.46%
ROIA	10.35%	0.84%
Profitability Index	1.99%	1.06%

Table 2.4: Simulation with different crop prices - Economic-Financial viability indicators for a typical integrated crop-livestock, continuous crop, and continuous livestock farm in Mato Grosso from 2005-2012

2.4- Discussion

2.4.1- The high profitability and greater profit stability of iCL under a range of scenarios offsets its high upfront costs

Despite its low uptake compared to continuous cropping system or traditional extensive ranching, our results indicate that iCL is a substantially better land use investment than continuous crop or livestock systems from a financial perspective under existing crop price scenarios. It both increases the productivity of pasture areas and reduces reliance on external inputs in cropping areas, contributing to higher overall profitability. One reason for the low uptake of iCL is that farmers accurately perceive the system to have high upfront costs and they are uncertain as to how long it will take for the system to pay back this investment (Cortner et al., 2019; Costa et al., 2012; Martha Júnior et al., 2011). However, our results show that the payback period is only 4 years for the iCL system, less than that of continuous cropping - 6 years, or continuous livestock - 5 years.

If payback time is considered as an investment risk indicator (Assaf Neto, 2011; Gitman and Zutter, 2014), then iCL actually demonstrates lower economic risk than continuous crop or livestock systems (Lazzarotto et al., 2010; Muniz et al., 2007). The iCL system also shows lower variations in profit and NPV under different price and interest rate scenarios. Given the high fluctuations in prices that have occurred in grain commodity prices over the 2000s and their inverse relationship to domestic beef prices, iCL allows farmers the opportunity to buffer their losses when one system suffers due to major price changes. However, the positive returns on continuous cropping are likely a market barrier to the adoption of iCL in regions that are highly suitable for soybean and corn production.

2.4.2- The economic performance of continuous cropping is highly dependent on exchange rates and world prices

Due to its dependence on external markets for both sales and fertilizers, the performance of continuous cropping was strongly influenced by the prevailing exchange rate and international commodity prices, the same main drivers of deforestation in the Amazon (Rodrigues-Filho et al., 2015). When the currency was devalued, Brazilian crops became more competitive in global markets, but, also faced higher production costs (Table 2.1). In 2008 and 2011, when the exchange rate increased substantially, production costs were particularly high.

Moreover, the high profitability of cropping under current price scenarios may explain why the most common strategy of iCL in this region has been the “third harvest”, in which a farmer produces soybean in the first harvest and plants corn intercropped with pasture. Recent research by Embrapa found that 83% of integrated systems in Brazil are iCL and the same pattern can be observed in Mato Grosso (Embrapa; Rede ILPF, 2017). Furthermore, the “third harvest” strategy represents around 50% of iCL in Mato Grosso (Embrapa; Rede ILPF, 2017). As the results showed, iCL can reduce external input dependence and improve the economic viability of farming in the region.

2.4.3- Extensive livestock ranching traps farmers in a cycle of low income due to dry season losses

The cash flow restrictions faced by traditional extensive livestock producers make it difficult for ranchers to take advantage of the livestock market. These farmers have few alternatives than selling part of their herd in the dry season, which limits their cash flow and, as a consequence, their capacity to generate revenue. The lack of economic competitiveness of extensive livestock relative to cropping or iCL explains why over the last decade in Mato Grosso many pasture areas have been overtaken by cropland (Lapola et al., 2014; Macedo et al., 2012).

Given the existing low returns of continuous livestock systems, and future potential changes in climate that will further reduce pasture productivity in Mato Grosso (Gil et al., 2018), it will be even more imperative to help farmers adopt improved pasture management practices, such as iCL to maintain their livelihoods, or else abandon production entirely. iCL would also help reduce the greenhouse gas emissions from livestock (Gil et al., 2018) and provide new funding opportunities, which have been connected with use and adoption of sustainable practices such as ABC Plan.

2.4.4- Low interest loans are key to the viability of establishing all three systems

Using the SELIC interest rate scenario of 19.24%, only iCL was still economically viable. Using the ABC interest rate of 5.5% doubled the NPV of iCL. Continuous cropping showed huge deficit in the SELIC interest rate scenario, indicating the relationship between technological levels and financial obligations. These results underscore the importance of public policies to provide attractive funding plans with low interest rates to agriculture. However, in recent years, because of economic and political crises, the interest rates provided by the ABC program increased to 8.5% in 2016/2017 and 7.5% in 2017/2018 (MAPA, 2017).

2.5- Conclusion

The challenge of protecting the environment, while generating income and reducing social inequality, requires the identification of agricultural strategies that enable the sustainable intensification of production. Given the growing international concern about the environmental impacts of agricultural activities in the Brazilian Amazon and Cerrado, as well as the importance of Brazilian agriculture in world food systems, the promotion of sustainable agricultural practices in Brazil is of global relevance.

This work, in addition to presenting an alternative to the current model of agriculture, sought to advance understanding of the economic performance of iCL as a sustainable intensification strategy compared to traditional continuous crop and livestock systems. Our results showed that iCL had higher levels of productivity, profitability, and return on investment and lower payback periods and economic risk than the continuous crop and livestock systems under existing prices and exchange rates over a 7 year period between 2005-2012. However, under higher crop prices, continuous cropping provides better economic results than the integrated system.

The case study approach used here is necessary and useful in the absence of a large sample of iCL farms from which to draw data, but does not guarantee that the results are representative of all potential iCL farms in the region. In order to assess how generalizable our results are to northern Mato Grosso and the rest of the Legal Amazon, a wider sample of farms across the region needs to be considered. As iCL continues to be adopted, these types of surveys will become increasingly possible.

Finally, the financial performance of iCL, though potentially important for decisions to adopt or not adopt these systems, are not the only outcomes that are relevant to farmers and policy makers. Systematic measurement of environmental indicators such as soil fertility, greenhouse gases emissions, and water consumption on iCL farms in the study region are needed. Further research should also explore the tradeoffs between economic and environmental outcomes in integrated systems (e.g., Gil et al. 2018). Since farmers are often motivated by non-monetary objectives and integrated systems entail major changes in management complexity, debt financing, and farm aesthetics, better understanding of their cultural appropriateness is needed (Garrett et al. 2017b; Cortner et al. 2019). Given the multifaceted and dynamic reality associated with agriculture, it is vital to assess the social and environmental benefits across a wider range of farms and regions, as well as climate and macroeconomic scenarios.

The evaluation of any agricultural system's potential to promote sustainable development must be based on models and assessments that capture the interrelations between different system components - economic, social and environmental - at broader spatial scales beyond the farm (Garrett and Rausch, 2016).

Acknowledgement

The authors thank Embrapa Agrosilvopastoral, Mato Grosso Institute of Agricultural Economics (IMEA) and the National Rural Learning Service - MT for the support and funding of this research. Moreover, we thank the Work Group of iCLF systems of Embrapa Agrosilvopastoral for fundamental collaboration in development of this economic analysis. We also thank all the colleagues and reviewers who helped with important advices for the text. Special thanks to Aisten Baldan for fundamental help with the reference search and Paula Emilia Pimentel for help with figures. Errors and limitations remaining are responsibility of the authors

2.6- Supplementary information

2.6.1- Construction of the Weighted Average Cost of Capital (WACC)

The construction of the WACC follows the structure:

$$WACC = w_1 \times k_1 + w_2 \times k_2 \qquad (1)$$

$$k_2 = (Jp - IPCA) + (\beta \times R_s) \qquad (2)$$

$$\frac{Jp = ((V_s \times S) + (250.000,00 \times (0,85 I_{CDB})))}{Cp} \quad (3)$$

$$Cp = I \times k_2 \quad (4)$$

In which:

W_1 = Participation of others' capital costs;
K_1 = Value of financial expenses;
W_2 = Participation of the cost of equity;
K_2 = Opportunity cost of equity;
Jp = Interest weighted, factor that considers both the risk sector as the producer's profile;
IPCA = official inflation index;
B = levered beta, risk indicator for an activity in relation to the systematic market risk
R_s = Risk premium associated with the sector of productive activity;
V_s = Amount invested in savings;
S = savings interest rate;
I_{CDB}= interest rate offered by Bank Deposit Certificates;
Cp = Monetary value of equity invested in the activity;
I= Total investment.

The final capital cost was defined as a balance between the equity portion, defined here as 60%, and the amount of capital financed, 40%[16]. It was used as interest rate for the funded portion the values practiced by the Center - West Constitutional Fund, 8.75%, in 2005. This was the main and the most used financing instrument available at that time. For the equity share, the final cost was defined as: R$ 250,000.00[17] capitalized by interest offered by Bank Deposit Certificates (CDB)[18] deducted from income tax, and the remaining portion was capitalized with reference to the official savings rate. The outcome of adjustment in the equity cost was discounted by official inflation index (IPCA) to get the real interest rate and added a risk measure for agriculture sector, defined as the difference between the return expected value on assets of agricultural companies operating in the main capital stock of Brazil, Bovespa, and the expected return of the market

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[16] These values were established after discussions with farmers and consultants who worked in the region in 2005.

[17] It was established in 1995 in Brazil, the Credit Guarantee Fund. This institution, linked to the National Monetary Council and the Central Bank, set rules and guarantees for investments in the capital market in Brazil. In the set of rules there is the definition of the maximum guaranteed to the creditor in events of financial difficulties of the agencies that are depositories of its resources. Currently, this value is R$ 250,000.00. For more information about this, visit: http://www.fgc.org.br/

[18] This bond is taken as a reference to the capital market brokers to define the expected return to be paid to its customers. The final amount was deducted from the income tax. CDB interest in 2005 was 17.56%.

portfolio with less risk.

2.6.2- Information about representative farms case studies

The approach used in the paper was to develop representative case studies for each of the agriculture systems evaluated based on the economic relevance of these agricultural systems for Mato Grosso (crop (soybean + corn) and livestock) and an alternative agricultural strategy (iCL) that has been encouraged by Brazilian government as a proposal for increase sustainable agricultural practices in the Amazon and Cerrado regions.

To ensure the representativeness, robustness and consistency of our data, besides the data collected in the controlled field experiment, we used regional data from Mato Grosso Institute of Agricultural Economics (IMEA), a research institution which carries out a comprehensive yearly economic survey in the main soybean, corn, cotton and beef cattle production regions in the state of Mato Grosso.

IMEA uses a worldwide consolidated methodology to elaborate regional reference farms for each commodity to provide accurate information of cost, revenue, productivity, investment and all necessary infrastructures to carry out the production activity. This approach consists of meeting with representatives from different society groups as indicated in the text. According with IMEA, to produce a final result for each region, they organize five focus group meetings, depending on region size and the economic relevance of the product. The audience size for each meeting includes roughly 80 - 100 people. The soybean meetings are bigger than others. By using regionalized data offered by IMEA to elaborate our representative farms, we ensure that our information presents the real situation observed by farmers.

To aid the accuracy in our findings, we checked all our results with farmer’s organization, consultants and trading managers and all of them were aligned with ours results. Unfortunately, we do not have access of survey instrument or other instruments used by IMEA.

2.6.3 – Economic Results Data

Discounted Cash flows and NOPAT - Integrated Crop and Livestock system - USD/hectare								
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Gross Revenue	**0.00**	**687.19**	**1295.52**	**1798.51**	**1374.12**	**2226.97**	**2164.64**	**2734.82**
Sales Taxes (-)	0.00	33.57	34.02	39.02	31.84	30.46	34.43	29.54
Net Revenue	**0.00**	**653.62**	**1261.50**	**1759.49**	**1342.28**	**2196.51**	**2130.21**	**2705.28**
Production Cost (-)	0.00	(787.93)	(921.32)	(1069.54)	(947.75)	(1392.43)	(1182.99)	(1875.71)
Gross Profit	**0.00**	**(134.31)**	**340.18**	**689.95**	**394.52**	**804.07**	**947.22**	**829.57**
Operating expense (-)	0.00	(21.94)	(26.81)	(31.33)	(34.76)	(36.21)	(32.45)	(44.25)
Operating Profit (EBIT)	**0.00**	**(156.25)**	**313.37**	**658.62**	**359.77**	**767.86**	**914.77**	**785.32**
Income Tax(-)	0.00		(84.09)	(178.53)	(96.40)	(207.71)	(248.56)	(210.52)
Net Operation Profit After Taxes	**0.00**	**(156.25)**	**229.28**	**480.09**	**263.37**	**560.16**	**666.21**	**574.80**
Depreciation (+)	0.00	8.62	10.93	13.57	13.55	13.92	10.50	16.37
Operating Cash Flow	**0.00**	**(147.63)**	**240.21**	**493.67**	**276.92**	**574.08**	**676.71**	**591.17**
Investment (-)	(863.38)							
Residual Value								646.41
Working Capital (-)								
Cash Flows	**(863.38)**	**(147.63)**	**240.21**	**493.67**	**276.92**	**574.08**	**676.71**	**1237.58**
Discounting Fator	1.00	1.10	1.20	1.31	1.44	1.58	1.73	1.89
Discounted Cash Flow	**(863.38)**	**(134.77)**	**200.20**	**375.60**	**192.35**	**364.03**	**391.74**	**654.04**
Pay back		(998.15)	(797.95)	(422.34)	(230.00)	134.03	525.77	1179.81

*** 2005 values**

Discounted Cash flows and NOPAT - Continuous Crop system - USD/hectare

	2005	2006	2007	2008	2009	2010	2011	2012
Gross Revenue		**545.52**	**723.10**	**1,035.87**	**891.74**	**890.90**	**1,113.32**	**1,168.68**
Sales Taxes (-)		30.18	33.63	36.76	30.78	28.71	33.66	35.72
Net Revenue (+)		**515.34**	**689.47**	**999.11**	**860.96**	**862.18**	**1,079.66**	**1,132.96**
Procutction Cost (-)		(471.27)	(530.57)	(586.83)	(588.91)	(505.56)	(521.54)	(623.00)
Gross Profit		**44.07**	**158.90**	**412.28**	**272.05**	**356.62**	**558.12**	**509.96**
Operating expense (-)		(100.53)	(111.24)	(120.72)	(125.48)	(121.88)	(126.05)	(129.76)
Operating Profit (EBIT)		**(56.46)**	**47.67**	**291.56**	**146.58**	**234.74**	**432.06**	**380.20**
Income Tax(-)			(1.54)	(71.89)	(32.31)	(54.83)	(109.10)	(92.51)
Net Operation Profit After Taxes		**(56.46)**	**46.13**	**219.68**	**114.27**	**179.91**	**322.96**	**287.69**
Depreciation (+)		20.74	23.20	25.54	25.63	21.75	17.76	18.07
Operating Cash Flow		**(35.72)**	**69.33**	**245.21**	**139.90**	**201.66**	**340.72**	**305.76**
Investment (-)	(765.63)							
Residual Value								573.23
Working Capital (-)								
Cash Flows	**(765.63)**	**(35.72)**	**69.33**	**245.21**	**139.90**	**201.66**	**340.72**	**878.99**
Discounting Fator	1.00	1.10	1.20	1.32	1.45	1.59	1.74	1.91
Discounted Cash Flow	**(765.63)**	**(32.57)**	**57.65**	**185.93**	**96.73**	**127.15**	**195.90**	**460.85**
Pay back		(798.20)	(740.55)	(554.61)	(457.88)	(330.73)	(134.83)	326.01

*** 2005 values**

Discounted Cash flows and NOPAT - Continuous Livestock system - USD/hectare

	2005	2006	2007	2008	2009	2010	2011	2012
Gross Revenue	**0.00**	**147.73**	**166.28**	**195.46**	**156.34**	**194.51**	**236.54**	**182.01**
Sales Taxes (-)	0.00	1.99	2.24	2.37	2.19	2.47	2.57	2.19
Net Revenue (+)	**0.00**	**145.74**	**164.03**	**193.09**	**154.15**	**192.04**	**233.98**	**179.82**
Production Cost (-)	0.00	(100.16)	(112.73)	(119.02)	(110.26)	(124.26)	(129.04)	(110.05)
Gross Profit	**0.00**	**45.59**	**51.31**	**74.07**	**43.88**	**67.78**	**104.94**	**69.77**
Operating expense (-)	0.00	(4.41)	(4.96)	(5.24)	(4.85)	(5.47)	(5.68)	(4.84)
Operating Profit (EBIT)	**0.00**	**41.18**	**46.35**	**68.84**	**39.03**	**62.32**	**99.27**	**64.93**
Income Tax(-)	0.00	(11.32)	(12.75)	(18.93)	(10.73)	(17.14)	(27.30)	(17.86)
Net Operation Profit After Taxes	**0.00**	**29.86**	**33.60**	**49.91**	**28.30**	**45.18**	**71.97**	**47.07**
Depreciation (+)	0.00	3.59	4.04	4.26	3.95	4.45	4.62	3.94
Operating Cash Flow	**0.00**	**33.44**	**37.64**	**54.17**	**32.25**	**49.63**	**76.59**	**51.01**
Investment (-)	(173.73)							
Residual Value								
Working Capital (-)								
Cash Flows	**(173.73)**	**33.44**	**37.64**	**54.17**	**32.25**	**49.63**	**76.59**	**51.01**
Discounting Fator	1.00	1.09	1.19	1.30	1.42	1.55	1.69	1.85
Discouted Cash Flow	**(173.73)**	**30.63**	**31.58**	**41.62**	**22.69**	**31.99**	**45.22**	**27.59**
Pay back		(143.09)	(111.52)	(69.90)	(47.20)	(15.21)	30.01	57.59

*** 2005 values**

CHAPTER 3

INTEGRATED CROP-LIVESTOCK SYSTEM: A SUSTAINABLE LAND-USE ALTERNATIVE FOR FOOD PRODUCTION IN THE BRAZILIAN CERRADO AND AMAZON

3- INTEGRATED CROP-LIVESTOCK SYSTEM: A SUSTAINABLE LAND-USE ALTERNATIVE FOR FOOD PRODUCTION IN THE BRAZILIAN CERRADO AND AMAZON

3.1- Introduction

Ongoing global changes in the interconnections between economic activities and environmental resources use are among the most relevant issues regarding the future of our society. A central challenge is to tackle the negative environmental impacts caused by agricultural production and, simultaneously, manage 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 agricultural production is expected to double to meet the increase in population which is forecasted to reach 9.8 billion people by 2050 (United Nations, 2017).

Considering that all economic activities are open subsystems, in which both energy and matter flows interplay; and given that the Earth is virtually a closed system in which energy can come in and go out, but not matter (Georgescu-Roegen, 1986, 1977, 1971), the emergy accounting proposed by Howard T. Odum (Odum, 1996) is a powerful tool to evaluate agricultural production systems, that operate at the interface between biosphere and technosphere, and 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 human society involved in all production - the “energy memory” (Brown and Ulgiati, 1997; Odum, 1996; Ulgiati et al., 2011). The emergy synthesis has been widely used to evaluate the efficiency and sustainability of agricultural production systems, e.g., 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).

The emergy accounting is an evaluation framework grounded in the hierarchical organization systems, 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; Odum, 1996, 1988). It provides concepts and evaluation procedures based on interrelation between nature and the economic subsystem, following the irreversible thermodynamics (Brown and Ulgiati, 1997; Ulgiati et al., 2011).

On a convergent view, Georgescu-Roegen's contribution to the 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). As technology-intensive agriculture has been increasing the demand for soil services beyond its carrying capacity, the upshot is the raising soil degradation observed worldwide (Davis et al., 2012; Foley et al., 2011; Graziano da Silva, 2010; Herrero et al., 2010; Reis et al., 2016). Moreover, Georgescu-Roegen's Fund-Flow model (Georgescu-Roegen, 1970) offers insightful instruments to understand this process. This analytical model gathers the productive factors into two categories: i) funds factors: are the structural elements - "Ricardian land"[19], human capital, and physical capital - which provide services in several processes that occur over time, represented by agents that transform inflows into outflows, are and ii) flows factors: which are inputs or outputs that are either produced or consumed during the operation of a system (Georgescu-Roegen, 1970).

Therefore, 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 (e.g., soil quality), 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;

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

Ehrlich, 1989; Foley et al., 2011).

It is under this context that Brazil is endeavoring to adopt integrated crop-livestock systems (iCL) and integrated crop-livestock-forest systems (iCLF) as a way to increase the efficiency and sustainability of its agricultural production, particularly in the Cerrado and the Amazon Biomes (Brasil, 2012a, 2010a). Integrated agricultural systems aim to improve sustainability through complementarities of various types of production (e.g. crops, livestock and forestry) on the same land area using intercropping or crop rotations to obtain synergies among agroecosystem components (Balbino et al., 2011; Lemaire et al., 2014; Macedo, 2009; Nair, 1991). Integrated systems represent a strategy for intensifying the use of resources - labor, land, and capital – to increase productivity, while diversifying production and sparing land (Franzluebbers, 2007; Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016). 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).

Previous studies in Brazil, mainly in the Cerrado, have also shown that iCL systems can increase production efficiency since they contribute to improvements in soil quality; water conservation; increase in animal performance and reduction in greenhouse gases emissions (Kluthcouski et al., 2003; Macedo, 2009; Oliveira et al., 2018; Salton et al., 2014; Vilela et al., 2011). However, information about iCL's as a feasible alternative from large-scale agriculture in the Amazon and Cerrado 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 in the Amazon region, an issue of global interest.

The objective of this paper is to evaluate the iCL systems as alternative for both conventional crop and livestock systems in Brazilian Cerrado and the Amazon region using emergy synthesis approach. In this analysis, we use data from an iCL system (soybean and beef cattle) farm versus typical crop rotation (soybean - corn) farm and typical livestock farm located in the state of Mato Grosso, the country's largest producer of soybean, corn, and beef cattle. Our analysis relies on one year of data (2017/18 season) and considers energy flows provided by renewable and nonrenewable resources, both internal and external, of productive systems. We also calculated a suite of economic outcomes including gross revenue, production cost, and profitability to complement our environmental analysis.

3.2- *Methods*

3.2.1- 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. 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, and it is the most important producer for soybean, corn, cotton, and beef cattle in Brazil (IMEA, 2020; MAPA, 2020). The cropping data for this study were gathering from the municipality of Sorriso, located in the Mid-North region of Mato Grosso (Figure 3.1). This region produces around 40% of all soybeans and corn of Mato Grosso. The livestock data were obtained from the municipality of Barra do Garças, in the Southeast region of the state (Figure 3.2). This region accounts for about 16% of the total herd of Mato Grosso (IBGE, 2020).

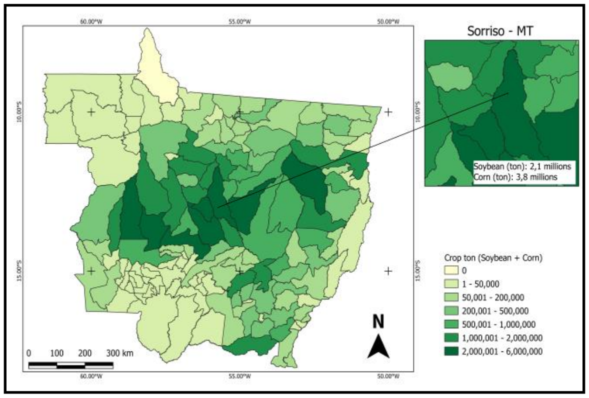

Figure 3.1: Crop concentration in Mato Grosso, 2017

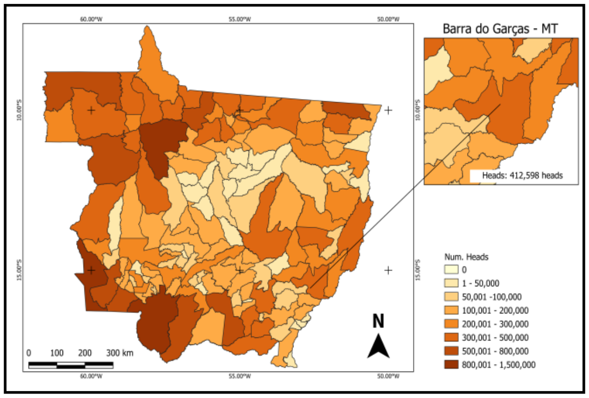

Figure 3.2: Livestock concentration in Mato Grosso, 2017

3.2.2- Systems description

Typical crop and livestock systems 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). 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 1,200 hectares 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 required for the operation of this continuous soybean/corn rotation was 1,196.11 USD[20]/ha, 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 level of technology, low productivity, and large land areas. Typical livestock farm size is 2,200 hectares 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.

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[20] 2018 prices (1 UDS = 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.

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 2,678 hectares 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, 1,078 hectares 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.

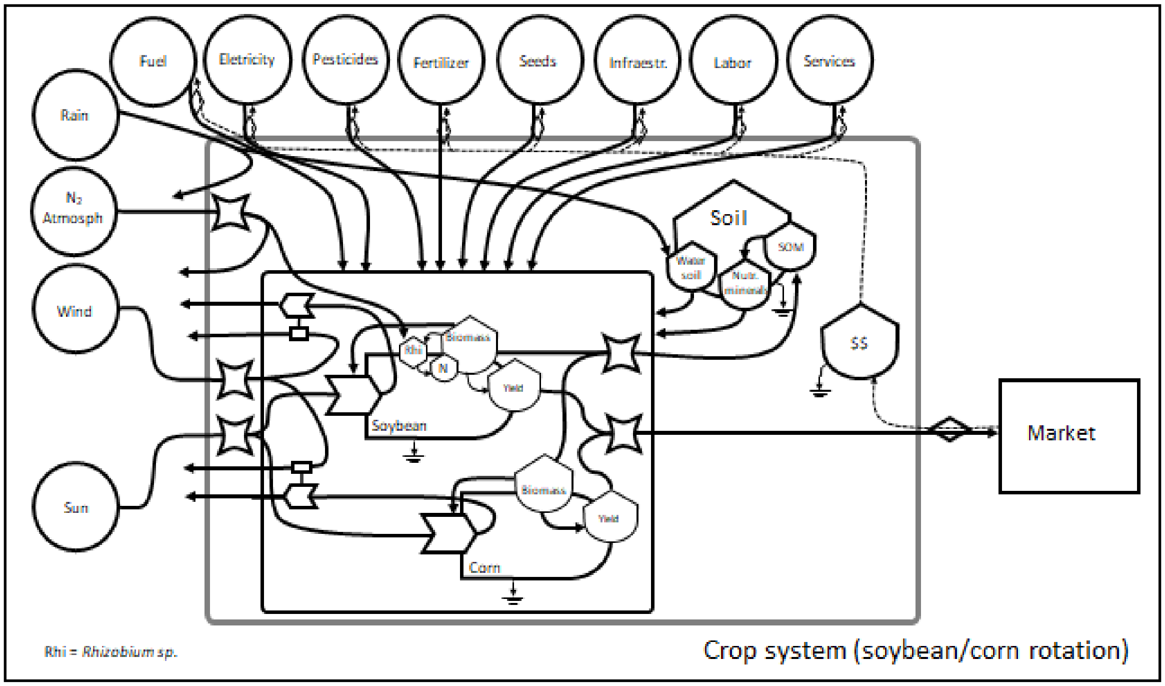
The animals are sold for slaughter when they reach 585 kg. Supplements are used all year long and included: i) mineral salt for breeding stock with an average consumption ranging between 67 and 100 g.day-1 and 100 and 150 g.day-1 according to animal weight in the rainy and dry season, respectively; ii) a ratio of 300g to each 100kg 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.

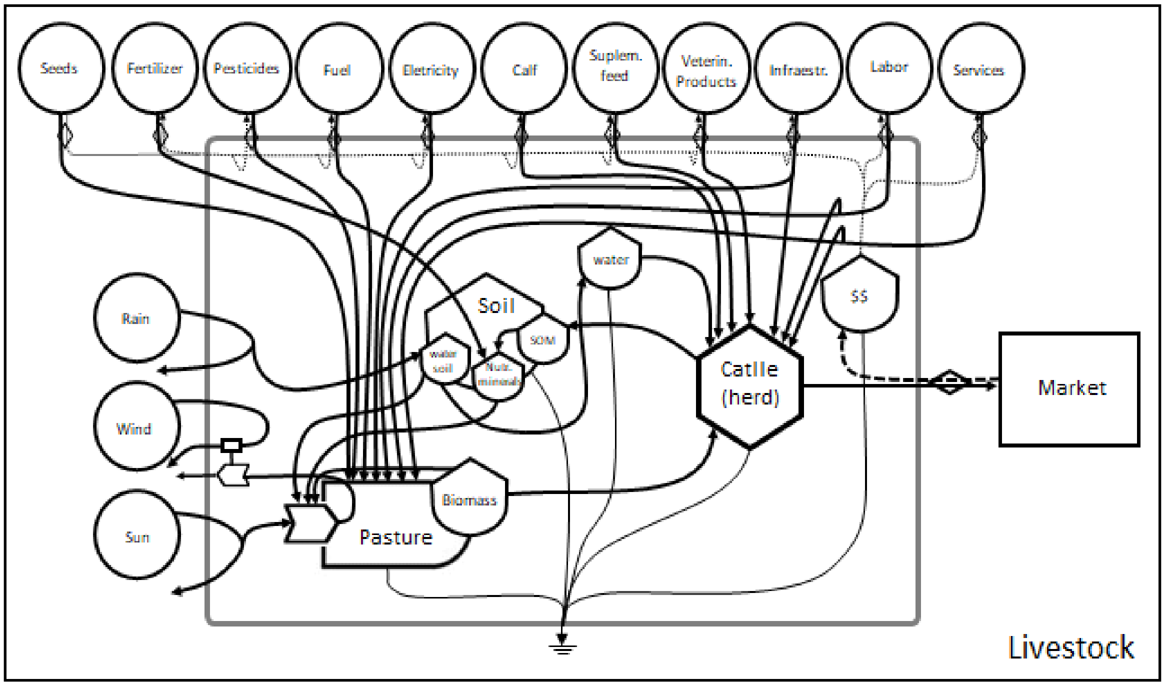
3.2.3- Observations about the emergy approach

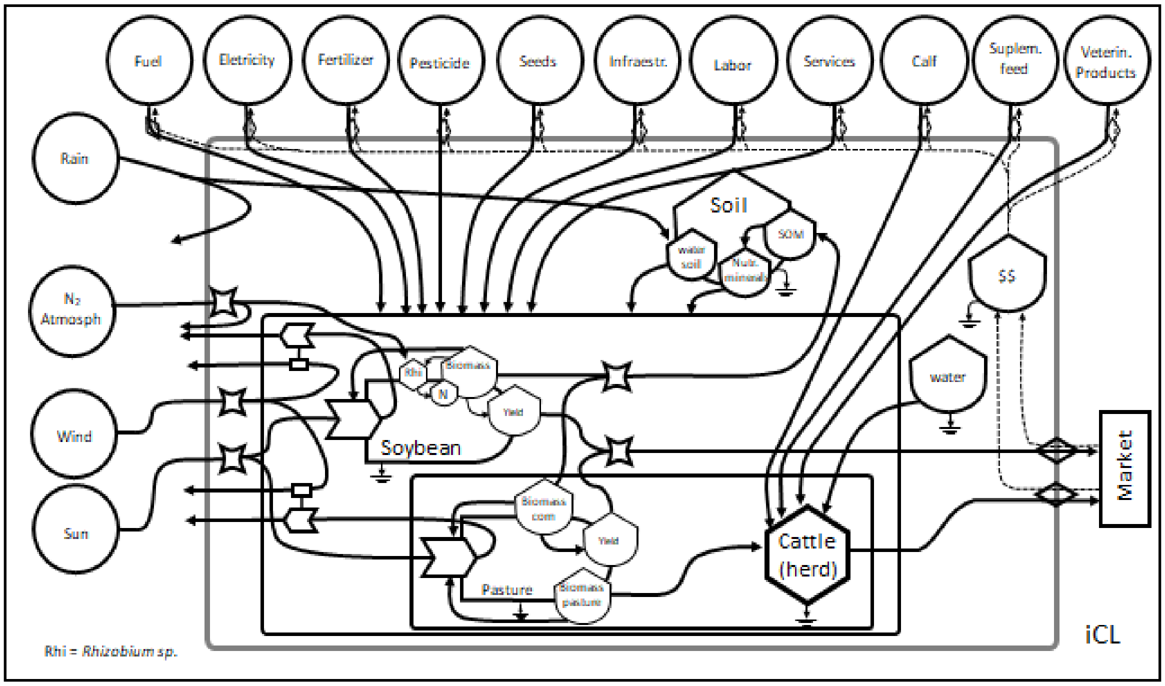
The emergy approach is a conceptual framework that offers tools to evaluate the contributions of environmental services (a donor-side perspective) that, in general, are not considered in the traditional economic analysis of production (Brown and Ulgiati, 2004, 1997; Odum, 1996, 1988), and provides a 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 (Figure

3.3) (Brown, 2004; Odum, 1996).







Source: Elaborated by authors
Figure 3.3: Energy flow diagrams for each production system

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 3.2). 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 activity 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 indicators used are summarized in (Table 3.1). All input flow data and index calculations were carried out in formatted spreadsheets (Rodrigues et al., 2002) available in the supplemental material.

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[21]	$A_{renew} + A_{non-renew}$	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)[22]	$\frac{CO_{2-eq}}{Y}$	Net ton $CO_{2\text{-eq}}$ emissions per unit yields measured in emergy	Sustainable systems contributes to reduce $CO_{2\text{-eq}}$ emissions

Source: (Brown and Ulgiati, 1997; Dong et al., 2018; Odum, 1996; Wright and Ostergård, 2016)
Table 3.1: Emergy Indicators

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[21] A detailed explanation of Emf formalization and calculations are in the supplementary material.
[22] A detailed explanation about CemI formalization and calculations are in the supplementary material.

3.3- Results

3.3.1 – Renewable resources

Mato Grosso state is located within the Amazon biome and presents high yearly precipitation rates, although submitted to a severe dry season from June to September. The rainfall is the main renewable resource available. Hence, management 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., 2009; Martin et al., 2006; Odum, 1996). The differences across the three production systems are remarkable. Evapotranspiration represents 25.7% (110.6 E+13 sej.year^{-1}) of the total emergy used by the integrated systems, 15.3% (71.5 E+13 sej.year^{-1}) by the crop system and 65.8% (113.7 E+13 sej.year^{-1}) by the livestock system. This number illustrates the heavy reliance on natural renewable resources by the traditional livestock system.

Another important renewable resource is atmospheric nitrogen (N_2) fixation provided by soybean. This biological feature of soybean 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 10.3% (43.9 E+13 sej.year^{-1}) of crop system emergy uses and 5.2% (22.5 E+13 sej.year^{-1}) for the integrated system. This item is absent from the livestock system entirely.

3.3.2- Non-renewable resources

The non-renewable resource considered for all three systems is topsoil losses. The estimated topsoil losses were: 1,509.5 kg.ha^{-1} for crop system, 898.3 kg.ha^{-1} for the integrated system, and 287 kg.ha^{-1} for the livestock system.

				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
NON-RENEWABLE 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	4.56E+03	1.40E+04	4.00E+01	1.12E+10	[6]	5.13	15.72	0.04
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	$	6.76E+01	1.34E+02	1.18E+01	4.26E+12	[10]	28.81	57.26	5.04
	Sum of purchased inputs							293.00	342.27	58.30
TOTAL EMERGY								430.45	466.98	172.78
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 E+24 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)

Table 3.2: Inputs, UEVs and Results

3.3.3- 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: 73.3% of all emergy used. Fertilizers and limestone represented the most important share of these external inputs: 48.9%. 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[23] in fertilizers was much higher and explaining the high productivity in the crop systems. 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 3.4% 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 (1.2 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}), 9.5% of all emergy. These are the major input 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 10.7%. 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}).

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

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 1.3% 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 (57.2 E+13 sej.year^{-1}) were twice the value for the integrated system (28.8 E+13 sej.year^{-1}) and ten times larger than for the livestock system (5.0 E+13 sej.year^{-1}).

3.3.4- Emergy indicators

The results for the set of indicators evidence the striking contrast between the crop system, heavily dependent on purchased external inputs, and the livestock system, essentially based on free local resources. In this scenario, the integrated system can be viewed as intermediate, showing a balanced apportionment between yield and resources used.

Indicators	Formulas	ICL	Crop	Livestock
% Renewable	**R/(R+N+P+S)**	0.31	0.26	0.66
Environmental Loading Ratio	**(P+S+N)/R**	2.23	2.91	0.52
Emergy Investment Ratio	**(P + S)/(N + R)**	2.13	2.74	0.51
Emergy Yield Ratio	**Y/(P + S)**	1.47	1.36	2.96
Non-renewable/Renewable	**(N + P)/R**	2.02	2.43	0.48
Empower Density	**sej/ha/yr**	4.30E+15	4.67E+15	1.73E+15
Emergy Sustainability Index	**EYR/ELR**	0.66	0.47	5.71
Transformity		1.30E+05	2.92E+04	1.75E+06
Emergy Footprint		8656.80	4691.95	3342.64
EmF (factor m)		3.23	3.91	1.52
CemI	**ton CO2eq/Y (J)**	-2.71E-11	3.70E-11	7.98E-09

Table 3.3: Emergy Indicators

The integrated system presented a renewable resource use of 31%, whereas the crop system showed 26% and livestock system 66%. The portion of renewable resources used is decisive to explain the higher ELR for the crop system: 2.91. The ELR for the integrated system was 2.23, and for the livestock system 0.52. These results indicate that the crop system impose 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 EIR for the crop system was 2.74, and for the integrated system it was 2.13. The best performance considering investment on external inputs was in the livestock, which presented the value of 0.51 for the EIR.

The EYR results demonstrate the net contribution to the economy from the productive systems. The crop system, even displaying higher productivity, presented the lesser 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 2.96. 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 ESI illustrates as the crop system presents an unbalanced performance, considering the economic and the ecological sub-systems. The value of 0.47 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 5.71. The ESI for the integrated system was 0.66.

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 3.91 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 needed area to provide all emergy used would be 3.23 times larger than its real size.

Lastly, the carbon-emergy indices evidence the potential of the integrated crop-livestock system to aid the Brazilian Government to achieve its international commitments in mitigating 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.

3.3.5 - 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 UDS ha$^{-1.}$ In contrast, the livestock system showed a net loss of 0.58 UDS ha^{-1}, while the integrated system a net profit of 235.69 UDS ha^{-1}.

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**

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

Table 3.4: Economic Results

3.4- Discussion

3.4.1- Technology-intensive agriculture and the Entropy law

The crop system’s higher reliance on external inputs and higher UEVs values for its main inputs such as fertilizers, pesticides, and seeds impose a heavier load 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. Considering that high production cost implies the need for higher productivity for the system to be economically viable, and assuming that the high productivity of the crop system is connected with specialization and large-scale production, the negative environmental impacts of this system tend to increase, in a vicious circle.

According to the Law of Entropy, higher emergy values imply higher energy dissipation (Georgescu-Roegen, 1973, 1971; Odum, 1996, 1988). If we consider that connected with energy consumption the crop system consumes a massive amount of raw materials, and that after leaving the productive system this matter is found under a degraded form (Georgescu-Roegen, 1977), the intensification of crop production exerts rising pressure to the Earth´s carrying capacity, mainly for absorption of wastes and greenhouse gases (Georgescu-Roegen, 1977). Taking into account that the Earth's carrying capacity is limited (Foley et al., 2011; Lambin and Meyfroidt, 2011; Steffen et al., 2015), the adoption of agricultural systems less dependent on external inputs while keeping high productive levels, as the integrated system, is a welcome initiative to promote sustainability.

Crop systems produce a high net yield. However, it displays significant adverse environmental impacts as demonstrated by ELR, ESI and Emf indicators. Similar results for crop systems performances are found in the literature (Barros et al., 2017; Martin et al., 2006; Ortega et al., 2005; Rótolo et al., 2015; Zhang et al., 2016). As a result, its integral cost, considering economic and environmental resources, tends to be higher than its societal benefits (Martin et al., 2006). This feature illustrates a lack of sustainable prospects in the long run for this production system (Ortega et al., 2005; Rótolo et al., 2015).

In contrast, the integrated system, even being dependent on the same set of inputs, presented a better balance between inputs consumption and yield, as demonstrated by its emergy indicators. Analogous integrated systems performance were observed in previous studies (Buller et al., 2015; Cavalett et al., 2006; Fonseca et al., 2016; Patrizi et al., 2018). The highest soybean productivity in the integrated system (4.2 tonnes.ha^{-1}) was reached using three times fewer fertilizers, while the crop system productivity was (3.6 tonnes.ha^{-1}). Possibly, the land use strategy - rotation soybean and pasture – contributes to increase soil organic matter content and, consequently, soil fertility (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}.

This improved productive performance in the integrated systems is more evident when considering beef cattle production, which was 75% superior to the traditional livestock production. Smart land-use strategy to provide nutritive pasture over the year, mainly in the driest period, and the utilization of industrialized feed explain this remarkable difference. However, the emergy account indicated the substantial share of supplement feed, 10.7 % of all emergy used. A possible adjustment to increase the efficiency of the integrated system and its long-run sustainability would be reducing its utilization of supplement feed by increasing its pasture support capacity.

3.4.2 – Integrated systems can improve the efficiency of the fund factors

The substantial differences across the evaluated systems in fertilizers use, in soil organic matter and productivity illustrate the environmental stress in the crop systems. The extensive use of external inputs to increase productivity intensify the pressure on free inputs (Davis et al., 2012; Martin et al., 2006; Martinelli et al., 2010). The negative consequences can be viewed on the non-renewable inputs, particularly soil. 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). Moreover, the soil organic content in the crop system is 25% lower than the value observed for the integrated system.

Following Georgescu-Roegen’s Fund-Flow model approach (Georgescu-Roegen, 1970), the crop system results suggest that this activity produces modifications in the fund factor soil, reducing its quality and, hence, its productive capacity. Since the soils’ productive services used are not replaced by the 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). Therefore, the strategy to maintain and increase productivity in the crop systems is deepening dependence on fertilizers.

On the other hand, the integrated system results suggest that the continued crop-livestock rotation has the potential to increase soil organic matter (Franzluebbers et al., 2014; Franzluebbers and Stuedemann, 2008; Herrero et al., 2010; Oliveira et al., 2018). Our findings corroborate the assumption of using integrated systems as an effective strategy to reclaim degraded pastures (Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011), as well as the assumption that the integrated system reduces external dependence on inputs and, simultaneously, increase soil quality (Franzluebbers, 2007; Herrero et al., 2010; Lemaire et al., 2014). 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 the rational use of environmental resources and promoting sustainable agricultural practices (Daly, 1997; Davis et al., 2012; Foley et al., 2011; Herrero et al., 2010; Reis et al., 2016).

3.4.3 – Economic results and emergy synthesis

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 highlights this issue. Even showing the highest production cost (977.77 USD/ha), the net profit for the crop system was 25% higher than the value for the integrated system. Therefore, the economic results indicate that the crop system is the best alternative for farmers to invest their money. On the other hand, the performance for the livestock system evidences its limited capacity to provide economic return. This issue explains the land-use change pattern in Mato Grosso over the latest years: many pasture areas have been replaced by croplands (Lapola et al., 2014; Macedo et al., 2012).

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) (Appendix 2). Comparative economic evaluation for agricultural systems in Mato Grosso showed that in a conjuncture of higher commodity prices, the crop systems demonstrate better economic performance than the integrated crop-livestock system. However, the integrated systems present better profitability in a scenario of low commodities prices (dos Reis et al., 2019).

Nonetheless, the economic results contradict the observed results 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). In a high commodity price scenario, the high efficiency of external inputs to be converted in final produce, and the large-scale production maintain the economic subsystem. However, this pattern is not a sustainable option. 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.

3.4.4 – Land Sparing and CO_2eq sequestration in the integrated crop-livestock systems

The adoption of more productive agricultural systems can be an effective policy to deal with land-use conflicts in the Amazon and Cerrado 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. These results are 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. The land sparing effect indicates the amount of area could be spared due to the use of more productive technologies, maintaining constant the amount of final production (Martha et al., 2012; Vieira Filho, 2018). 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.

The Brazilian Government has been encouraging the adoption of the integrated systems as a public policy to establish sustainable agricultural practices in the Amazon and Cerrado regions as presented in the ABC Plan (Brasil, 2012a), in the National Climate Change Policy (NCCP) (Brasil, 2010), as well as in the Nationally Determined Contribution (NDC) to the Paris Agreement (2015). Moreover, the integrated systems is considered a central technology to achieve CO_2 reduction targets defined in the NCCP - reductions ranging from 36.1% to 38.9% of the emissions forecasted until 2020 - (Brasil, 2012a, 2010a). 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 Amazon and Cerrado, the contribution of this system to minimize agriculture CO_2 emissions can be immense (Carvalho et al., 2010; Gil et al., 2018; Strassburg et al., 2014). On the other hand, the livestock results evidence the massive contribution of this activity for Brazilian agriculture emissions, and the rancher’s challenge to increase productivity and improve resource use efficiency (Buller et al., 2015; Gil et al., 2018; Strassburg et al., 2014; zu Ermgassen et al., 2018).

3.5- Final remarks

This paper highlighted the Brazilian initiative of integrated crop-livestock system adoption and applied the emergy synthesis approach originally proposed by Odum (1996) to evaluate and compare the environmental-economic performance between the integrated crop-livestock system with two most used land-use strategies in Mato Grosso: a typical crop system (soybean – corn rotation) and a typical (extensive) livestock system.

Our results indicated that the integrated system is an effective land-use strategy for grain and beef production in the Cerrado and Amazon biomes in Mato Grosso state, Brazil, since it displayed better performance in capturing renewable resources and transforming them into final products. In addition, while the integrated system it is less dependent on external inputs such as fertilizers, pesticides, and fossil fuels, it also recovers soil quality and reduces soil losses when compared with the crop systems. In contrast, the typical crop system, in spite of its better economic performance, showed heavy environmental load due to its excessive dependence on external inputs. The traditional livestock system showed negative economic performance and limited capacity to transform its dotation of renewable resources into outputs, a consequence of its lower technological level. Moreover, our findings confirm the higher participation of livestock in CO_2 emissions by Brazilian agriculture.

However, considering the shortcomings of the emergy approach such as discussed by Hau and Bakshi (2004), some aspects can be further developed to improve this work: i) increase the dataset by building a time series analysis for the three systems to enhance the understanding about the positive and negative outcomes of each one; ii) improve data description as to identify the extent of inputs renewability for inputs from outside the system's boundary; iii) the economic analysis presented considered only the commercial output of each system. This approach could be enhanced by examining the ecosystem services provided by the agroecosystems; and iv) some UEVs used were built for agricultural systems and productive conditions different than those evaluated in this paper. Since agriculture is a crucial economic activity, particularly in Brazil, and considering the vital relevance of 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.

Finally, our results suggest that public policies focused on supporting the widespread adoption of integrated systems can be an effective instrument to encourage sustainable use of environmental resources in Brazilian agriculture, as well as, to promote sustainable agricultural systems in Cerrado and the Amazon biomes.

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3.6- Supplementary information

3.6.1- Emergy Footprint Index

The used approach to evaluate the emergy footprint follows the previous works of (Agostinho and Pereira, 2013; Björklund and Johansson, 2012; Wright and Ostergård, 2016; Wright and Østergård, 2015).

The emergy footprint can be defined as the theoretical area needed considering that all resources used by a production system were stem from local renewable resources (Björklund and Johansson, 2012; Wright and Ostergård, 2016). This definition is closely with the concept of supported area presented by (Agostinho and Pereira, 2013): the supported area or carrying capacity of a natural or human-dominated system can be determined by that environment's ability to supply the required emergy.

In order to determine the emergy footprint the supported area is expressed as the land area required supporting an economic activity solely on a renewable base. It is obtained by dividing the total emergy input to a system by the average Renewable Empower Density of the region in which it is located (Agostinho and Pereira, 2013).

To emphasize the connections of the productive systems considered in this work with global market and illustrates the dependence of external inputs, issue that impacts the sustainability of the agricultural systems, the spatial division of inputs suggested by (Wright and Østergård, 2015):

- ✓ on-site: the productive site area
- ✓ local: resources from the neighborhood area, in our evaluation, we considered local products from Mato Grosso state
- ✓ non-local: resources originated outside Mato Grosso state

Each input can be classified as renewable (R_i) or nonrenewable (N_i) where i = represents each spatial category: on-site, local, non-local. Considering that, $R_{on\text{-}site}$ = R and $N_{on\text{-}site}$ = N, the estimation of the theoretical land area required is concerned about the purchased resources (PR). Therefore, for each PR input a spatial classification was determined considering its respective local origin of input (l_i = 1 or 0).

To determine the contribution on each input for the respective renewable empower density, a literature review provided the on-site renewability fraction (r_i) for each input described in Tab. 2. For each spatial level the renewability of flow was calculated using the formulas provided by (Wright and Østergård, 2015):

$R_{local} = \sum r_i \times l_i \times PR_i$ (1)

$R_{non\text{-}local} = \sum r_i \times (1 - l_i) \times PR_i$ (2)

The global renewability of inputs (R_{global}) is determined by the formula:

$R_{global} = R_{on-site} + R_{local} + R_{non-local}$ (3)

The footprint of an agriculture system can be described as the sum of two areas: A_{renew} = the on-site land area plus the estimated area associated with the renewability fraction of local and non-local inputs and $A_{non\text{-}renew}$ = the theoretical land area required if the equivalent emergy provided by purchased non-renewable resources was obtained by a renewable flow corresponding the agriculture systems location.

The formalization of emergy footprint is:

$$EmF = A_{renew} + A_{non-renew} = \sum \frac{R_i}{R_{empi}} + \sum \frac{N_i}{R_{empi}} \quad (4)$$

Where i = on site, local and non-local.
Follow (Wright and Ostergård, 2016), we assume that on-site and local renewable empower density are similar. For non-local inputs, we used the global empower density:

$$\text{emergy input to the planet Earth per year} / \text{area of planet Earth} = \frac{12.1\,\mathrm{E}+24\,\mathrm{sej}}{5.10\,\mathrm{E}+10\,\mathrm{ha}} \quad (5)$$

The baseline used was 12.1 E+24 sej/year (Brown et al., 2016).

Finally to define the demand of land for each agriculture system, we used the equation:

$$m = \frac{EmF}{A} \quad (6)$$

Where (A) is the on-site original area of each agriculture system and (m) is the emergy overshoot factor.

3.6.2- Greenhouse gas emission on farm

The calculus for Greenhouse gases (GHG) emissions were performed using the official methodology provided by Brazilian Government (Ministry of Science, Technology, Innovation and Communications) to elaborate its official inventory of Greenhouse gas emissions to be presented in the United Nations Framework Convention on Climate Change (UNFCCC) meetings.

The complete description of procedures can be found in (Ministry of Science Technology Innovation and Communications, 2015), and all values used can be found in the SAMEframe spreadsheet made available as supplementary material.

We adapted this framework in the study case used in this research considering the inputs used in the productive process as follows:

- ✓ We use the International Panel of Climate Change (IPCC) Fifth Assessment Report values (the most recent reference) to convert all GHG gases in $CO_{2eq.}$ A conversion table and additional explanations can be found here: https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

- ✓ The items considered and formulas are presented below. Information considered were TIER 2:

1- Direct GHG emission

A- Synthetic Nitrogen Fertilizers

$N_2O_{Fert} = N_{Fert} x(1 - FRAC_{Gasf})xEF_1$

N_{Fert} = amount of synthetic nitrogen used (kg)

$FRAC_{Gasf}$ = % of volatilized nitrogen in NH_3 and NO_x forms

EF_1 = emission factor (%)

B- Limestone

$CO_{2Limestone} = (Q_{Calcitic} xEF_{Calcitic} + Q_{Dolomitic} xEF_{Dolomitic})x44/12$

$Q_{Dolomitic}$ = amount of Dolomitic limestone (kg)

$EF_{Dolomitic}$ = emission factor (% carbon in limestone)

C- Urea

$CO_{2Urea} = (Q_{Urea} xFE_{Urea})x44/12$

Q_{Urea} = amount of urea (kg)

EF_{Urea} = emission factor (% carbon in urea)

D- Animal waste in pasture

$N_2O_{pasture} = NAxN_{ex} xFRAC_{PRP} xEF_3$

NA = number of animals by category

N_{ex} = amount of nitrogen excreted by category (kgN/animal year)[24]

$FRAC_{PRP}$ = % of excreted nitrogen on pasture

EF_3 = emission factor (%)

Category	N_{ex} (kgN/animal year)
< 1 year	12
1 year< x <2 years	24
> 2 years	40

E- Enteric Fermentation

$CH_{4Fermentation} = NAxFE_{CH_4Fermentation}$

NA = number of animals by category

$FE_{CH_4Fermentation}$ = CH_4 emission factor (kgCH_4/animal)

CH_4 emission factor (kgCH_4/animal) – Mato Grosso, Brazil		
Male	Female	Calf
55	66	42

F- Animal waste management

$CH_{4AW} = NAxEF_{CH_4AW}$

NA = number of animals by category

EF_{CH_4AW} = CH_4 emission factor (kgCH_4/animal)

CH_4 emission factor (kgCH_4/animal) – Mato Grosso, Brazil		
Male	Female	Calf
1.3	1.2	1.6

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[24] The values for this item are Tier 1 Guidelines IPCC (2006)

G- Harvest residues

$$N_2O_{\mathrm{Re}s} = (CROP_i xFRAC_{DMCrop} x \frac{RES_{DM}}{CROP_{DM}} xFRAC_{NC\,\mathrm{Re}s})xEF_1$$

$CROP_i$ = total production of crop (i). In this calculus i = soybean and corn

$FRAC_{DMCrop}$ = % of dry mass of each crop

$\frac{RES_{DM}}{CROP_{DM}}$ = relation between dry residual and dry mass for each crop

$FRAC_{NC\,\mathrm{Re}s}$ = % of nitrogen in each crop plant

EF_1 = emission factor (%)

Crop	$\frac{RES_{DM}}{CROP_{DM}}$	$FRAC_{NC\,\mathrm{Re}s}$	$FRAC_{DMCrop}$	
soybean	1.98	0.009	0.087	Tier 2
corn	1.48	0.008	0.87	Tier 2

H- Machinery

$$CO_{2Diesel} = Q_{Diesel} xEF_{Diesel}$$

Q_{Diesel} = amount of diesel used (L)

EF_{Diesel} = emission factor (kgCO$_2$/L)

2- Secondary source of N_2O emissions

A- Atmospheric deposition

$$N_2O_G = ((N_{Fert} xFRAC_{Gasf}) + (N_{\mathrm{Re}sidual} xFRAC_{Gasm}))xEF_3$$

N_{Fert} = amount of synthetic nitrogen used (kg)

$FRAC_{Gasf}$ = % of volatilized nitrogen in NH_3 and NO_x forms

$N_{\mathrm{Re}sidual}$ = residual nitrogen available after deposition of NH_3 and NO_x

$FRAC_{Gasm}$ = % of volatilized residual nitrogen in NH_3 and NO_x forms

EF_3 = emission factor for atmospheric deposition (%)

I- Leaching

$$N_2O_L = ((N_{Fert} + N_{\mathrm{Re}sisual})xFRAC_{Leach}))xEF_4$$

N_{Fert} = amount of synthetic nitrogen used (kg)

$N_{\mathrm{Re}sidual}$ = residual nitrogen available after deposition of NH_3 and NO_x

$FRAC_{Leach}$ = % of nitrogen loss by leaching

EF_4 = emission factor for N_2O by leaching

This approach informs the gross GHG emission on farm.

To calculate the net $CO_{2eq.}$ emission for each agriculture system, we use the carbon sequestration factors provided by (Carvalho et al., 2010). Taking into account the particularities to determine carbon stocks dynamics in agricultural soils, these factors were suitable since they were calculated in the same region, and for the same production systems evaluated in this research.

It is noteworthy that in the net CO_{2eq} emission calculus we do not consider GHG soil's emission since our literature review did not find appropriate references to be used.

Finally, the carbon emergy output intensity (CemI) index was calculated considering the net CO_{2eq} emission and the total energy produced on each system following (Dong et al., 2018).

CHAPTER 4

ASSESSING AGRICULTURAL SUSTAINABILITY IN THE BRAZILIAN AMAZON AND CERRADO REGIONS USING FUZZY LOGIC APPROACH

4- ASSESSING AGRICULTURAL SUSTAINABILITY IN THE BRAZILIAN AMAZON AND CERRADO REGIONS USING FUZZY LOGIC APPROACH

4.1- Introduction

The increasing complexity and the intensification of interactions across humans, the economic sector, and the environmental resources, as well as the enhancement of their negative impacts such as increase of poverty, income concentration, and climate change suggest that the global society need to settle a different development trajectory (Brundtland, 1987; Davis et al., 2012; Foley et al., 2011; Godfray et al., 2010; IPCC, 2013; Steffen et al., 2015; United Nations, 2015). A fundamental issue is to implement a development process based on balance interrelationship between economic growth and environmental resources use having as main goal to promote society well-being (Graziano da Silva, 2010; Mebratu, 1998; Munasinghe, 1995; Sachs, 1986; Veiga, 2008). This is the central idea of sustainable development (Ayres, 1993; Brundtland, 1987; Mebratu, 1998; Sachs, 1986; Veiga, 2008).

The sustainable development concept encompasses three interlinked dimensions: economic, social and environmental (Brundtland, 1987; Dasgupta, 2010; Pearce et al., 1996; Purvis et al., 2019; Sachs, 1986; Veiga, 2008) and has as major goals: i) increase economic growth to eradicate poverty; ii) permanent innovation on productive sectors to improve efficiency reducing energy and resource consumption; iii) attend human essential necessities as job, food, energy, water and sanitation; iv) preserve environmental resources; v) encourage technological development and manage risks and, v) include the environment as a central issue on public policy (Becker, 1997; Brundtland, 1987; Dasgupta, 2010; Mebratu, 1998; Mueller, 2007; Pearce et al., 1996, 1994; Purvis et al., 2019).

In spite of being a global consensual objective, the implementation of strategies to promote sustainable development has been little effective (Foley et al., 2011; Godfray et al., 2010; IPCC, 2013; Steffen et al., 2015). According to Intergovernmental Panel on Climate Change (IPCC), scenarios for the next 100 years show perspectives for increasing the global temperature from 1ºC to 8.5ºC as consequence of anthropic activities (IPCC, 2013). The current worldwide land use strategies and the economic sector performance illustrate that the prevailing development process will not provide enough outcomes to enable the global society to achieve the Millennium

Development Goals indicated in the 2030 Agenda (United Nations, 2015).

In this context, agriculture assumes an essential function on a global scale in the solution to the crucial social problem: increasing food production to meet an increasing demand and, at the same time, promoting the preservation of natural resources (Davis et al., 2012; dos Reis et al., 2019; Foley et al., 2011; Godfray et al., 2010; Steffen et al., 2015). In addition, it is noteworthy mentioning the decisive and direct function of agriculture to achieve the Sustainable Development Goals (SDGs): i) end poverty in all its forms everywhere (SDG 1); ii) ending hunger, achieving food security and improving nutrition, promoting sustainable agriculture (SDG 2) and; iii) taking urgent action to combat poverty, climate change and its impacts (SDG 13) (United Nations, 2015).

Nonetheless, over the last fifty years, the technological revolution in agriculture to increase productivity based on widespread adoption of external inputs such as machinery, fertilizers, and pesticides has shown, as counterpart, substantial negative impacts in soil depletion, water contamination and greenhouse gas (GHG) emissions (Davis et al., 2012; Foley et al., 2011; IPCC, 2013; Pretty, 2008). This impacts are globally relevant since agriculture cover 38% of the Earth surface, the most extensive land use activity in a global level, it is the first user of water and the second contributor to the climate change, 24% of the total GHG emissions (Davis et al., 2012; Foley et al., 2011; IPCC, 2013). As a result, sustainable agricultural productive systems have increased their relevance worldwide (Davis et al., 2012; dos Reis et al., 2019; Foley et al., 2011; R. Garrett et al., 2017; Gil et al., 2018; Herrero et al., 2010; Lemaire et al., 2014).

Following this perspective, the Brazilian Government has been showing great interest in the research, improvement and dissemination of on farm practices that enhance economic results in agriculture and, simultaneously, contribute to the reduction of the social and environmental negative impacts associated with this activity, notably in Cerrado and the Amazon regions (Brasil, 2012a). Afterward the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP-15), the Brazilian Government indicated climate change mitigation actions with potential GHG reduction ranging from 36.1 to % 38.9 in relation to projected Brazilian emissions by 2020 (Brasil, 2012a). In addition, the commitments described in the Sectoral Climate Change Mitigation and Adaptation Plan for the Consolidation of a Low Carbon Economy in Agriculture (ABC Plan) (Brasil, 2012a), refer to actions to promote sustainable agriculture in Brazil. Finally, succeeding Brazil's ratification of the Paris Agreement in 2016, targets were set for the agriculture sector's contribution to reduce GHG emissions by 2030 (Brasil, 2016).

As a common issue in these initiatives, especially in view of the significant contribution of agriculture sector to Brazilian CO_2 emissions, responsible for 31.3% of direct emissions in 2015 (SIRENE, 2017), it is the commitment to increase the areas of integrated crop-livestock-forest systems (ICLF), particularly in the Amazon and Cerrado regions. These agriculture systems aim to improve the sustainability of agriculture production 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; Herrero et al., 2010; Lemaire et al., 2014; Macedo, 2009; Nair, 1991).

Integrated systems represent a strategy to intensify resource uses - labor, land, and capital – to increase productivity, diversifying production and sparing land use (Franzluebbers, 2007; Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016). Furthermore, integrated systems can be used to recover degraded pastures areas by using crop residual fertility and crop revenues to restore soil quality and fund further system improvements (De Oliveira et al., 2013; Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011). Prior studies in Brazil, mainly in Cerrado regions, have also shown that integrated crop-livestock systems (ICL)[25] can increase production efficiency since they contribute to: i) improvements in soil quality; ii) water conservation; iii) an increase of animal performance; and iv) a reduction in GHG emissions (Kluthcouski et al., 2003; Macedo, 2009; Oliveira et al., 2018; Salton et al., 2014; Vilela et al., 2011).

However, there is a lack of information about the iCL’s potential to be used as a feasible

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[25] Integrated crop-livestock systems are the most adopted in Brazil (83%), mainly in Brazilian Cerrado and the Amazon region (Embrapa; Rede ILPF, 2017).

alternative to boost sustainable agriculture systems in Cerrado and the Amazon regions (Macedo, 2009; Salton et al., 2014; Vilela et al., 2011). The literature review showed that, even being a promising strategy of sustainable agriculture system, research in ICLF system in Brazil has focused on specific aspects - economic, social or environmental - of the productive system, and not in to build a comprehensive approach to evaluate its potential to promote sustainable agriculture (dos Reis et al., 2019; Oliveira et al., 2014, 2018; Salton et al., 2014; Vilela et al., 2011).

As hard as to implement strategies to promote sustainable development is to measure it, since sustainable development is an inherently vague, ambiguous and fuzzy concept (Becker, 1997; Cornelissen et al., 2001; Mebratu, 1998; Phillis et al., 2010; Phillis and Andriantiatsaholiniaina, 2001), comprises conflicting interests and does not represent the endpoint of a process, rather, it represents the process itself (Becker, 1997; Hansen, 1996; Mebratu, 1998; Shearman, 1990). Furthermore, and considering sustainable agriculture systems, its conceptualization is time, scale and region dependent, ranging from specific soil attributes on the farm field to international trading arrangements and distribution mechanisms for agricultural commodities at a global level (Hansen, 1996; Pretty, 2008; Schaller, 1993; Smit and Smithers, 1993; Van Passel and Meul, 2012). Therefore, models to evaluate sustainability are essentially incomplete, since human perceptions, human expectative and available knowledge change over time (Cornelissen et al., 2001; Gómez-Limón and Sanchez-Fernandez, 2010; Sachs, 1986; Schaller, 1993; Shearman, 1990; Smit and Smithers, 1993).

Taking into account the increasing society concern about sustainability and the vast set of issues that this concept comprises, innumerous models and approaches to assess sustainability have been proposed. A comprehensive review of quantitative methods to assess sustainability can be found in Mallampalli et al. (2016), Ness et al. (2007), and Phillis et al. (2010). Considering agriculture sustainability at the farm level, de Olde et al. (2016), Schader et al. (2014), van der Werf and Petit (2002) and Van Passel and Meul (2012) offer an overview of indicator-based approaches to assess the sustainability performance in the food systems considering farms, farming systems and supply chains.

In this study, we focus on the farm level and relate sustainability with production activities and their social, economic and environmental outcomes (Cornelissen et al., 2001; Gómez-Limón and Sanchez-Fernandez, 2010; Hansen, 1996; Sattler et al., 2010; Schaller, 1993; van der Werf and Petit, 2002). Therefore, it is considered sustainable those agricultural systems that preserve or enhance the productive capacity of the environmental resources used, reduce biodiversity loss, display positive economic return, generate increasing levels of social welfare (Hansen, 1996; Pretty, 2008; Schaller, 1993) and, simultaneously, do not harm their capacity to continue over time (Foley et al., 2011; Godfray et al., 2010; Hansen, 1996; Herrero et al., 2010; Smit and Smithers, 1993).

Since sustainability of agriculture systems associate continuous interrelationship across context-dependent economic, ecological and societal (EES) issues (Becker, 1997; Cornelissen et al., 2001, 2003; Mebratu, 1998; Sachs, 1986; Smit and Smithers, 1993), the threshold between sustainability and unsustainability is not sharp, but rather fuzzy (Becker, 1997; Hansen, 1996; Mebratu, 1998; Munda et al., 1994; Phillis and Andriantiatsaholiniaina, 2001; Smit and Smithers, 1993). Approaches based on crisp sets for EES attributes imply that the policy makers can make a sharp, unambiguous distinction between sustainable and unsustainable process (Becker, 1997; Hansen, 1996; Klir and Folger, 1988; Pretty, 2008). However, strict conclusions are incompatible with the numerous uncertainties confronted in sustainable development assessments (Dunn et al., 1995; Munda et al., 1994; Phillis and Andriantiatsaholiniaina, 2001; Prato, 2005).

A suitable approach to assess sustainability is using fuzzy logic to develop sustainability indicators (Cornelissen et al., 2001; Dunn et al., 1995; Liu, 2007; Ocampo-Duque et al., 2006; Phillis and Andriantiatsaholiniaina, 2001; Prato, 2005). Proposed by Zadeh (1965), the fuzzy approach is an useful tool to deal with problems in which the source of imprecision is the absence of sharply defined criteria (Klir and Yuan, 1995; Kosko, 1990; Zimmermann, 2001). The Fuzzy set approach may be characterized as an extension of Classical set theory (Zadeh, 1989, 1965). In fact, the Classical set theory and its Boolean membership rules - 0: the element does not belong to the set; 1: the element belong to the set - can be described as specific case of comprehensive Fuzzy set approach (Klir and Yuan, 1995; Kosko, 1990; Zadeh, 1989, 1965; Zimmermann, 2001). In the Fuzzy approach each element can assume a continuous degree of membership in a set, ranging from 0 to 1 (Zadeh, 1989, 1965).

Fuzzy inference is especially valuable where approaches are built based on experts' knowledge (Cornelissen et al., 2003; de Vos et al., 2013; Liu, 2007; Zadeh, 1989). Furthermore, it permits to relate human expectative and knowledge about sustainability, expressed in EES issues, to linguistic variables (Cornelissen et al., 2001; Dubois and Prade, 1998; Kosko, 1990; Sami et al., 2014; Zimmermann, 2001), and translate them in sustainability indicators. Fuzzy approach is suitable to combine qualitative and quantitative information from a variety of scales (de Vos et al., 2013; Dunn et al., 1995) and offers a numerical assessment of sustainability (Cornelissen et al., 2001; Dubois and Prade, 1998; Phillis and Andriantiatsaholiniaina, 2001; Prato, 2005).

Sustainability assessment literature offers examples of Fuzzy inference approach usage to evaluate distinct agricultural production systems (Cornelissen et al., 2001; Gao and Hailu, 2012; Liu et al., 2013; Ocampo-Duque et al., 2006; Sami et al., 2014; Santos et al., 2017; Sattler et al., 2010). The main contribution of these studies illustrates the feasibility of Fuzzy approach to associate a set of qualitative and quantitative information from different dimension and scales in an summarized presentation of results, enhancing its meaningfulness and simplifying policy makers and farmers decisions about policies and practices to promote sustainable agriculture. However, the literature review indicated few studies focused on farm level information. Moreover, most of them use case studies approach to validate the assessment model proposed and do not rely on performance evaluation of different agriculture systems.

The objectives of this paper are to develop a comprehensive model based on Fuzzy approach to assess agricultural sustainability at farm level, and to compare different agriculture systems in state of Mato Grosso, the Brazilian leader in crop and livestock production. We used a survey to collect data from 22 farms in different regions of Mato Grosso (Figure 4.1), categorized into the three most representative agricultural systems adopted in this state: i) crop system rotation (soybean and corn); ii) livestock and; iii) integrated crop-livestock systems (ICL), and developed partial indicators from economic, environmental and social dimension and an overall sustainability index considering 2018/2019 season. These indexes were used to evaluate if the integrated systems can be considered an efficient alternative for large-scale crop systems and extensive livestock systems to promote sustainable agriculture practices in Cerrado and the Amazon regions.

4.2- Methods

4.2.1- Study region

The analysis focuses on agricultural productive systems located in the state of Mato Grosso, Brazil, one of the largest and most productive agricultural frontiers in the world (IBGE, 2020; IMEA, 2020; MAPA, 2020). Mato Grosso spans three ecological biomes: the Amazon, Cerrado, and Pantanal (Figure 4.1), and it is the leading crop and livestock producer in Brazil: 28% of soybean, which represents 10% of world soybean production, 33% of corn and 71% of cotton productions are cultivated in Mato Grosso (IMEA, 2020). Furthermore, 15% of Brazilian beef cattle herd, 30.1 million of heads, are bred in Mato Grosso pastures (IBGE, 2020). This remarkable agricultural production performance represented a Gross Value Added (GVA) of USD 20.5 billion[26] in 2018/2019 season (IMEA, 2020) due to intense commercialization with external market, especially China and Arab countries (MAPA, 2020).

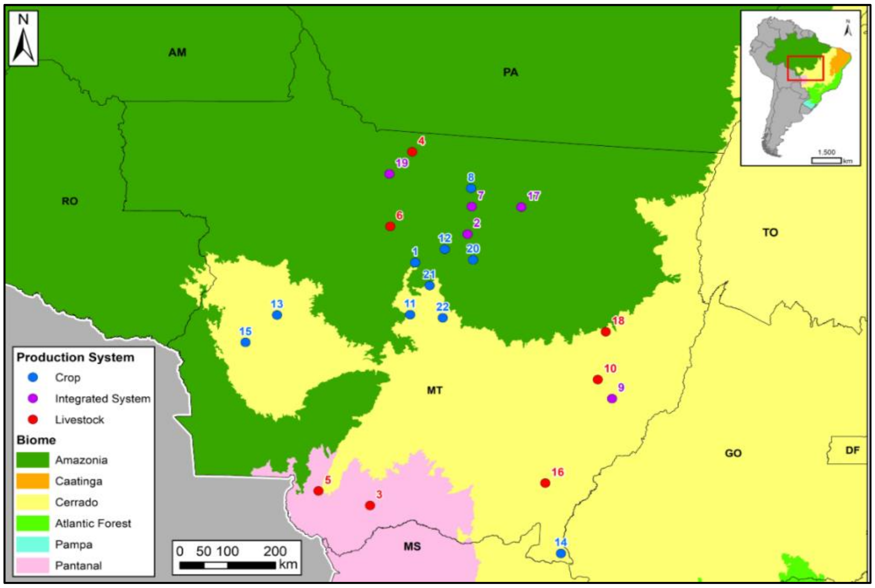

Figure 4.1: Farms evaluated

Nonetheless, these economic results present, as counterpart, considerable negative environmental

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[26] 2019 prices (1 UDS = 3.94 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.

impacts, particularly deforestation (Andersen et al., 2002; Barona et al., 2010; Hargrave and Kis-Katos, 2013; Malhi et al., 2008). Mato Grosso is one of the majors responsible for deforestation in the Amazon region. Only in 2019, 1,685 Km^2 of forest was deforested in Mato Grosso, representing 18% of deforestation in the Brazilian Amazon that year (INPE, 2020). Moreover, recent public and private investments in commercialization infrastructure in the Amazon Southeast region such as the conclusion of asphalt surfacing of the BR-163 until waterways on Tapajós River in Pará, reducing transportation cost to send commodities to Europe and China, and the implementation of big traders silos and warehouses in export ports in Santarém and Miritituba, also in Pará, has intensified conflicts and rose pressure to expand agriculture areas adjacent to BR-163. In 2018/2019 season, Mato Grosso allocated 23 million hectares to livestock and 16 million hectares to crops (IMEA, 2020). Therefore, the adoption of sustainable agricultural systems in this region has implications not only for Brazil, but rather for global society.

2.2- Some issues about Fuzzy Set Theory

Sustainable development assessment implies value judgment commonly formulated in linguistic variables which are inherently Fuzzy sets (Becker, 1997; Cornelissen et al., 2001, 2003; Dubois and Prade, 1998; Munda et al., 1994; Phillis and Andriantiatsaholiniaina, 2001; Smit and Smithers, 1993). Therefore, a suitable model to evaluate sustainable development needs to connect the subjectivity and the ambiguity of the linguistic variables to a numerical (crisp) value to indicate the contribution level of the available information to promote the sustainable development. The Fuzzy set approach offers this model structure (Dubois and Prade, 1998; Klir and Yuan, 1995; Munda et al., 1994; Phillis and Andriantiatsaholiniaina, 2001; Prato, 2005).

Considering that between the certainty of belonging and the certainty of not belonging to a specific set - binary logic -, there are infinite degrees of uncertainty - Fuzzy logic - (Kosko, 1992, 1990; Zadeh, 1989, 1965). Fuzzy approach provides a soft threshold to determine the degree to which an event occurs, not if it occurs (Cornelissen et al., 2001; Klir and Yuan, 1995; Kosko, 1992; Zimmermann, 2001). In the Fuzzy set framework, a linguistic variable $\tilde{A}$ is described by: i) base variable x of $\tilde{A}$, its domain; ii) name of $\tilde{A}$; iii) linguistic value $\tilde{A}_i$ of $\tilde{A}$ (i=1, 2…,n) and, iv) membership function $\mu_{\tilde{A}i}$ of $\tilde{A}_i$ (Cornelissen et al., 2001; Klir and Yuan, 1995; Zadeh, 1975).

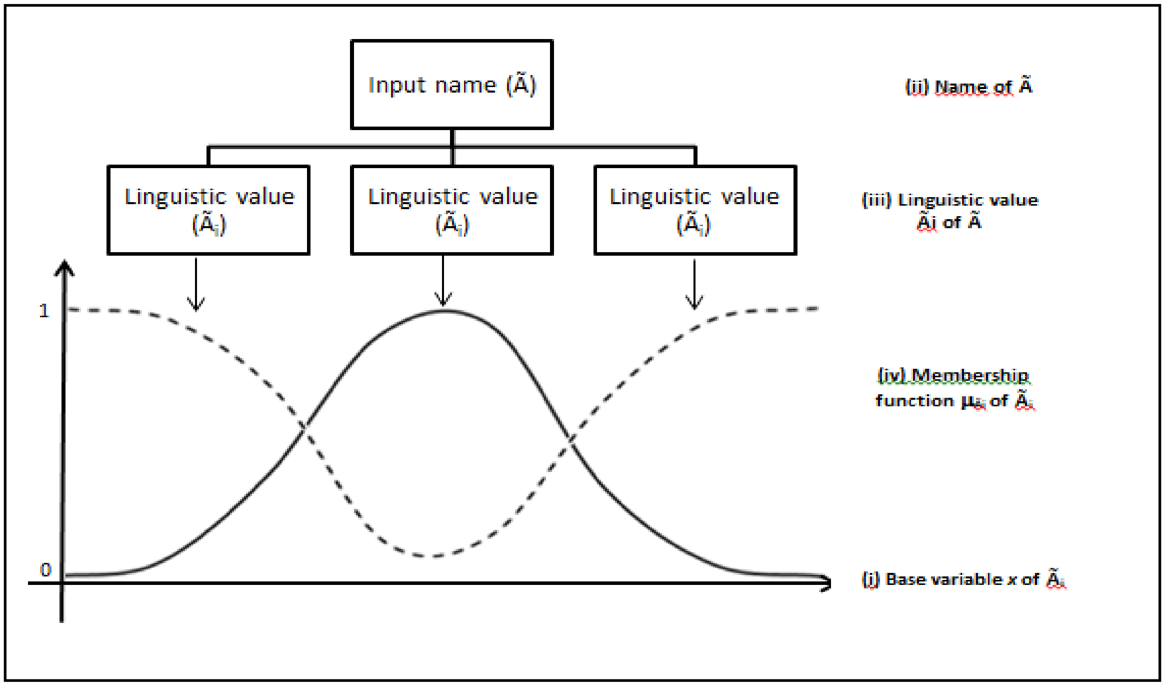

Figure 4.2: Linguistic variable

Membership functions are at the core of fuzzy models (Cornelissen et al., 2001; Klir and Yuan, 1995; Kosko, 1992; Zadeh, 1965; Zimmermann, 2001). It defines the soft thresholds, the gradual membership of each element *x* into the interval [0,1], and enables to assess the contribution of each element or indicator using functions to operate linguistic variables (Cornelissen et al., 2001; Klir and Yuan, 1995; Zimmermann, 2001). Many types of curves, linear and non-linear, are used for building membership functions (Kosko, 1990; Pedrycz, 1994; Phillis and Andriantiatsaholiniaina, 2001). Taking into account the subjectivity on membership function construction and their relevance for the assessment model (Klir and Yuan, 1995; Kosko, 1992; Zadeh, 1975; Zimmermann, 2001), we based our membership function choice on literature review, scientific knowledge and appropriateness regarding variable set.

Fuzzy model inference system has basically four steps (Dubois and Prade, 1998; Klir and Yuan, 1995; Kosko, 1992, 1990; Zimmermann, 2001), as follow:

- ✓ Fuzzification: process to convert a crisp value *x* of an input variable to a value of membership in a Fuzzy set identified by a linguistic variable. A Fuzzy set is defined for each indicator;
- ✓ Application of the Fuzzy rule base: Fuzzy rules are created applying approximate reasoning based on expert's knowledge and human perception to represent the connection across the fuzzy variables using linguistic proposition. The fuzzy rules offer a gradient of results. In this model we use if-then proposition. The if-part contains the premise and the then-part contains the conclusion;
- ✓ Fuzzy Inference: process to analyze the fuzzy rules. The rules relate the antecedents (if-part) to formulate a consequent result (then-part), and a final output of the evaluation system;
- ✓ Defuzzification: the mathematical process in which the Fuzzy sets are converted to a single crisp value.

2.3- Fuzzy model to assess agriculture sustainability in Mato Grosso

The framework proposed is an indicator-based approach and it was built as a hierarchical fuzzy inference system (Liu, 2007; Phillis and Andriantiatsaholiniaina, 2001; Sami et al., 2014) developed using MATLAB Fuzzy Logic Toolbox (Figure 4.3). The model structure provides a partial indicator for each EES dimension and an overall sustainability index (SI) for each farm. This structure is useful because it permits comparison across different agricultural systems and offers information to evaluate the contribution of each variable or dimension to the final result. The evaluation criteria for all indicators and indexes is based on the fuzzy inference structure in a direct way: higher values are associated with higher contribution to sustainability (Cornelissen et al., 2001; Liu, 2007; Prato, 2005; Sattler et al., 2010). To build the partial indicators and the overall index were assumed that all information displays the same relevance. Thus, any weighting rule as applied.

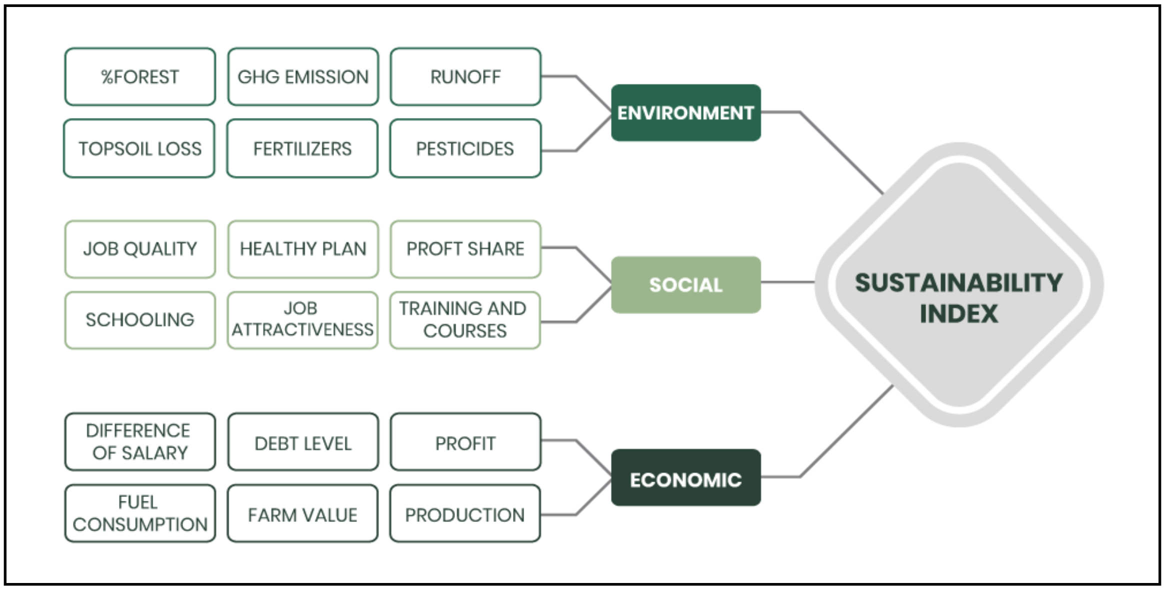

Figure 4.3: Fuzzy Inference System representation

The selection of variable set was carried out taking into account: i) the farm as the analysis level; ii) the three main sustainability axis: economic, environmental and social; iii) the availability of information; iv) the possibility to replicate this evaluation in different regions and contexts; v) the appropriateness in different agriculture systems to permit comparison and; vi) the representativeness of this indicator set to assess sustainability in the agriculture sector (Bossel, 2002; Gómez-Limón and Sanchez-Fernandez, 2010). Details about variable set are available on supplementary material.

The choice of membership function is context dependent and expresses the available knowledge about the problem to be evaluated (Dubois and Prade, 1998; Klir and Yuan, 1995; Pedrycz, 1994; Zimmermann, 2001). Our literature review indicated that triangular membership functions are the most used in evaluation of sustainability because: i) they are easy to manipulate; ii) they are consistent with EES information; iii) they can approximate most non-triangular ones and; iv) the higher computational requirement for more elaborated membership function does not imply better results (Cornelissen et al., 2001; Pedrycz, 1994; Phillis and Andriantiatsaholiniaina, 2001).

The efficiency and robustness of the fuzzy model strongly depends on the number of fuzzy sets used in the mapping process since it enables more continuity to the universe of discourse (Ocampo-Duque et al., 2006). To permit more differentiation among farms, we used five categories to translate inputs into linguistic variable: Very Low (VL); Low (L), Medium (M); High (H) and Very High (VH). Details about fuzzy set and fuzzy rules construction are presented on supplementary material.

The Fuzzy inference method defines the operational form of the Fuzzy model and the output of the Fuzzy system (Cornelissen et al., 2001; Phillis and Andriantiatsaholiniaina, 2001; Sattler et al., 2010). Fuzzy set literature offers a large variety of inference methods (Dubois and Prade, 1998; Klir and Yuan, 1995; Zimmermann, 2001). We chose the method MIN-MAX (Mamdani, 1977; Mamdani and Assilian, 1975), since it is the most suitable to represent expert's knowledge, it is the most used in environmental assessment, and it does not require elaborate computational resources (Cornelissen et al., 2001; Prato, 2005; Sattler et al., 2010).

Defuzzification process identifies a crisp value associated with the Fuzzy set built in the Fuzzy inference process (Cornelissen et al., 2001; Dubois and Prade, 1998; Kosko, 1990; Prato, 2005). We chose the center of gravity method because it is the most common (Dubois and Prade, 1998; Klir and Yuan, 1995; Kosko, 1990; Zimmermann, 2001). The output crisp value divides the area under the curve built in the MIM-MAX inference process into two equal parts representing the mean value of all curves generated in the inference step (de Vos et al., 2013; Liu, 2007; Ocampo-Duque et al., 2006; Sattler et al., 2010). Furthermore, the final crisp result indicates the membership in the Fuzzy set that describes the partial indicators and the overall sustainability index. (Klir and Yuan, 1995; Kosko, 1990; Zimmermann, 2001).

4.3- Results

4.3.1- Input set: economic, social and environmental data

Table 4.1 displays the input set used to build the partial indicators and the overall sustainability indexes for the 22 farms evaluated. The farms are distributed in the three biomes: the Amazon, Cerrado, and Pantanal, (Figure 4.1), and show a wide variability in terms of size, technological level, production system adopted and productive efficiency. To consider the efficiency in inputs usage, the environmental inputs were calculated as ratio of the produced energy by using the SAMeframe (Rodrigues et al., 2002) to convert final products in energy (joules). For the economic dataset, monetary inputs were built as ratio of the farm area.

Farm Code	Productive System	Farm Area (ha^{-1})	Biome	Economic					
				Profit (USDha^{-1})	Debit Level	Difference of Salary	Production (Jha^{-1})	Farm Value	Fuel Consumption (Lha^{-1})
1	Crop	1928	Amazon/Cerrado	396.34	0.72	3.44	2.35E+11	0.38	1.53E-10
2	ICL	5000	Amazon	426.05	0.01	3.44	2.06E+11	35.89	3.01E-11
3	Livestock	4560	Cerrado/Pantanal	3.09	0.75	1.03	4.63E+07	0.32	4.01E-09
4	Livestock	1000	Amazon	142.40	0.25	1.03	7.81E+09	2.03	3.81E-10
5	Livestock	3150	Amazon/Cerrado/Pantanal	43.61	0.75	2.06	4.54E+08	0.34	3.66E-09
6	Livestock	410	Amazon	70.30	0.76	1.03	1.72E+09	0.39	2.93E-09
7	ICL	7000	Amazon	384.01	0.06	3.44	2.30E+11	7.05	4.26E-11
8	Crop	1200	Amazon	351.39	0.55	1.03	1.77E+11	0.37	5.32E-11
9	ICL	200	Cerrado	561.43	0.00	2.06	1.58E+11	0.71	2.99E-10
10	Livestock	740	Cerrado	24.82	0.71	1.03	8.54E+08	0.41	3.55E-09
11	Crop	300	Amazon/Cerrado	415.73	0.00	3.44	1.85E+11	0.40	4.90E-11
12	Crop	3660	Amazon	481.72	0.00	1.03	1.60E+11	0.38	2.41E-11
13	Crop	5200	Amazon/Cerrado	1351.28	0.64	4.13	1.90E+11	0.34	8.66E-11
14	Crop	3000	Cerrado	739.63	0.00	5.16	2.24E+11	0.38	8.42E-11
15	Crop	815	Cerrado	291.28	0.40	5.16	1.92E+11	0.52	6.88E-11
16	Livestock	570	Cerrado	39.86	0.11	1.03	6.87E+08	5.23	4.28E-09
17	ICL	1000	Amazon	969.92	0.43	3.44	2.13E+11	0.81	1.52E-10
18	Livestock	600	Amazon/Cerrado	27.60	0.11	0.69	4.79E+08	5.47	6.14E-10
19	ILF	20000	Amazon	129.61	0.00	8.60	9.46E+10	0.39	3.55E-11
20	Crop	500	Amazon	730.27	0.84	1.55	1.85E+11	0.34	3.11E-11
21	Crop	5300	Amazon/Cerrado	656.02	0.00	3.44	1.78E+11	0.42	2.21E-10
22	Crop	13347	Amazon/Cerrado	656.62	0.00	5.16	2.20E+11	0.38	4.12E-11

Farm Code	Productive System	Farm Area (ha^{-1})	Biome	Social					
				Schooling	Family labor	Training and Courses	Job Quality	Healthy Plan	Profit Share
1	Crop	1928	Amazon/Cerrado	16	0.47	1	2.20	0	1
2	ICL	5000	Amazon	16	0.51	1	2.00	0	1
3	Livestock	4560	Cerrado/Pantanal	11	0.75	0	3.00	0	0
4	Livestock	1000	Amazon	16	1.20*	1	5.50	0	0
5	Livestock	3150	Amazon/Cerrado/Pantanal	16	1.20*	0	3.00	0	0
6	Livestock	410	Amazon	11	1.00	1	1.00	0	0
7	ICL	7000	Amazon	4	1.00	2	3.67	0	0
8	Crop	1200	Amazon	11	0.59	2	2.00	0	0
9	ICL	200	Cerrado	11	0.56	0	1.33	0	1
10	Livestock	740	Cerrado	8	0.78	1	0.67	0	0
11	Crop	300	Amazon/Cerrado	8	0.83	2	2.00	0	0
12	Crop	3660	Amazon	11	1.20*	0	3.25	0	1
13	Crop	5200	Amazon/Cerrado	16	0.48	4	12.00	1	0
14	Crop	3000	Cerrado	16	1.20*	1	12.00	0	1
15	Crop	815	Cerrado	11	1.00	1	2.25	0	0
16	Livestock	570	Cerrado	16	0.36	0	1.20	0	1
17	ICL	1000	Amazon	16	0.39	2	3.33	0	1
18	Livestock	600	Amazon/Cerrado	9	0.42	3	0.00	0	1
19	ILF	20000	Amazon	16	0.53	9	40.00	0	0
20	Crop	500	Amazon	8	0.33	0	0.67	0	1
21	Crop	5300	Amazon/Cerrado	8	1.20*	12	2.25	1	0
22	Crop	13347	Amazon/Cerrado	16	0.53	2	4.55	0	1

*Farm did not present any family member as employee. Was attributed the value 1.20 to simplify the calculus.

Farm Code	**Productive System**	**Farm Area (ha^{-1})**	**Biome**	**Environment**					
				Topsoil loss (kg J^{-1})	**Fertilizers (kg J^{-1})**	**Pesticides (kg J^{-1})**	**% Forest on farm***	**GHG emission (tonCO$_{2eq}$ J^{-1})**	**Runoff**
1	Crop	1928	Amazon/Cerrado	6.43E-09	8.55E-10	1.22E-11	0.22	2.40E-11	0.71
2	ICL	5000	Amazon	4.36E-09	1.37E-09	1.60E-11	0.18	-1.45E-11	0.48
3	Livestock	4560	Cerrado/Pantanal	6.20E-06	0.00E+00	0.00E+00	0.63	1.31E-07	0.10
4	Livestock	1000	Amazon	3.68E-08	3.92E-09	1.36E-11	0.75	1.38E-09	0.41
5	Livestock	3150	Amazon/Cerrado/Pantanal	6.33E-07	1.56E-09	1.56E-10	0.34	1.51E-08	0.10
6	Livestock	410	Amazon	1.67E-07	6.74E-09	6.69E-11	0.48	5.24E-09	0.40
7	ICL	7000	Amazon	3.90E-09	1.01E-09	1.91E-11	0.49	-8.97E-12	0.47
8	Crop	1200	Amazon	8.53E-09	1.48E-09	8.47E-11	0.63	3.37E-11	0.65
9	ICL	200	Cerrado	5.70E-09	1.87E-09	2.95E-11	-0.15	1.29E-11	0.41
10	Livestock	740	Cerrado	3.36E-07	2.49E-09	1.04E-09	-0.23	8.81E-09	0.31
11	Crop	300	Amazon/Cerrado	8.17E-09	2.14E-09	2.57E-11	0.22	3.25E-11	0.59
12	Crop	3660	Amazon	9.42E-09	2.21E-09	1.53E-11	0.63	3.83E-11	0.61
13	Crop	5200	Amazon/Cerrado	7.94E-09	1.85E-09	2.19E-11	0.10	3.11E-11	0.60
14	Crop	3000	Cerrado	6.75E-09	1.59E-09	2.71E-11	0.02	2.67E-11	0.50
15	Crop	815	Cerrado	7.84E-09	1.78E-09	5.54E-11	0.33	3.13E-11	0.71
16	Livestock	570	Cerrado	4.18E-07	4.24E-08	5.03E-11	0.05	1.08E-08	0.32
17	ICL	1000	Amazon	4.21E-09	4.28E-10	5.79E-11	0.38	-8.18E-12	0.48
18	Livestock	600	Amazon/Cerrado	5.99E-07	0.00E+00	3.79E-10	0.02	1.49E-08	0.31
19	ILF	20000	Amazon	2.51E-09	8.52E-12	9.40E-12	0.15	-1.48E-09	0.39
20	Crop	500	Amazon	8.17E-09	1.84E-09	3.17E-11	0.62	3.22E-11	0.59
21	Crop	5300	Amazon/Cerrado	8.50E-09	1.51E-09	1.91E-11	-0.08	3.39E-11	0.62
22	Crop	13347	Amazon/Cerrado	6.85E-09	1.55E-09	3.48E-11	0.13	2.76E-11	0.62

* Negative values indicate that the farm presented forest area bigger than the value determined by Brazilian Forest Code

Table 4.1: Economic, Social and Environmental inputs

The crop farms are characterized by a continuous soybean-corn system. They present, in general, the largest areas, the longest period in this activity, the biggest gross profits and high salary levels. The high technological practices used in these farms can be inferred considering their highest production cost due to the higher values for external inputs as fertilizers, pesticides and fuel. As consequence, these farms present the highest production levels. In addition, the crop farms use more management systems to improve financial and operational activities and show the highest values for courses and training activities.

In contrast, the livestock farms can be described by large areas, low technological level, low productivity and poor environmental and economic performance. Livestock farms presented the lowest gross profits, the highest debit levels and the lowest salaries. They showed the poorest results for the environmental dimension, particularly, in GHG emission. Moreover, even using small amount of fertilizers and pesticides in absolute terms, an indicative of low technological productive systems, the highest values for the ratios fertilizer/produced energy and NPK/produced energy for livestock farms evidence their poor productive performance.

For the integrated systems set, we can observe good results for social and environmental dimension and an intermediate position for the economic data. The integrated system farms presented higher market value, indicating the monetary gains due to the investment in infrastructure and the rising of the land prices in these productive systems. Moreover, these farms showed high productive level and higher efficiency in inputs usage. They displayed the lowest topsoil losses, lower values for fertilizers and pesticides use, the lowest value for GHG emission and high value for % forest indicator. For social inputs, the integrated system displayed high values for owner’s schooling, for job quality, for courses and training activities and profit sharing.

3.2- Sustainability indexes

Partial indicators and overall sustainability indexes are displayed in (Table 4.2). The fuzzy inference model generated a similar pattern for the all EES partial indicators: high values for crop and integrated systems farms and lower values for livestock farms. As a result, livestock farms presented the lowest values for the SI. Even the livestock farm that uses high technological practices, such as pasture management, genetic improvement and feedlot system, (farm number #4), it does not display SI higher than none crop or integrated system farm. In fact, this farm presented moderate performance for economic and social dimensions. However, its poor environmental performance explains its low SI.

Farm Code	Productive System	Economic	Social	Environmental	Sustainability Index
1	Crop	40.00	40.00	67.34	40.00
2	ICL	90.78	40.00	67.50	66.91
3	Livestock	6.89	20.75	40.00	21.17
4	Livestock	40.00	21.09	20.00	21.38
5	Livestock	7.00	21.29	20.00	5.48
6	Livestock	6.94	20.75	20.57	5.47
7	ICL	81.65	20.52	67.50	50.19
8	Crop	27.75	40.00	40.00	28.99
9	ICL	67.39	27.25	67.19	47.78
10	Livestock	6.30	14.38	40.00	19.34
11	Crop	67.42	20.64	40.00	40.00
12	Crop	67.40	20.75	40.00	40.00
13	Crop	40.00	67.33	40.00	40.00
14	Crop	67.27	40.00	67.19	66.69
15	Crop	67.27	20.75	40.00	40.00
16	Livestock	20.20	40.00	20.00	21.38
17	ICL	67.50	67.00	67.50	66.69
18	Livestock	20.22	40.00	40.00	21.40
19	ILF	67.23	67.21	90.50	92.58
20	Crop	40.00	32.50	40.00	40.00
21	Crop	67.14	40.00	67.41	66.69
22	Crop	72.58	66.86	67.22	66.84

Table 4.2: Partial Indicators and Overall Sustainability Indexes

The crop farms displayed the best results for some economic variables such as profit, debit level and production. Moreover, for the social dimension, the crop farms showed higher values for family labor, job quality and profit sharing. However, the comprehensive evaluation provided for the fuzzy indicators highlights the relevance of balance performance to promote sustainability. As a result, the integrated systems farms presented higher values for both, economic and social, indicators. The major contrast between crop farms and integrated systems farms was in the environmental index. The superior environmental performance of the integrated system farms explains the top ranking position for this group on the SI.

4.4- Discussion

4.4.1- ICLF systems and Brazilian's leadership in global commodities market

Brazil is an important player in global commodity market and, differently from its main competitors, has alternatives to increase the area allocated in agriculture and, particularly, has real possibility to improve its agriculture productivity. Given the great concerns about deforestation growth in the Brazilian Amazon region and its negative impacts on climate change (Barona et al., 2010; Coe et al., 2013; Fearnside, 2005; Lapola et al., 2014; Malhi et al., 2008), finding sustainable alternatives to raise agriculture productivity, intensifying the use of already available area, is the central issue for Brazil take advantage of its natural endowments, and reinforces its position in global commodity market.

Livestock farms can improve considerably their productivity (Gil et al., 2018; Strassburg et al., 2014; zu Ermgassen et al., 2018). Brazil allocates huge area for pastures - 180 million hectares -, and a large part of them - 35% - are in degraded situation (LAPIG, 2018), mainly in Cerrado and the Amazon regions. Degraded pastures imply low productive level and are responsible for negative environmental impacts such as high GHG emission and topsoil loss (de Oliveira Silva et al., 2016; Gil et al., 2018; Strassburg et al., 2014). Our environmental results for livestock farms evidence this scenario. The integrated systems can be used to recover degraded pastures and, simultaneously, increase livestock production in a sustainable way (Kluthcouski et al., 2003; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011). The average productivity of the integrated system farms was 35% higher than livestock farms (Table 4.3). Moreover, the integrated systems farms showed considerable difference from livestock farms in GHG emission, a key issue for Brazilian government to promote sustainability in agriculture and accomplish the GHG reduction targets internationally assumed.

Farm Code	Productive System	Production (Joules)	Soybean	Corn	Beef Cattle	Bean	Wood (teak)
			Production (Tonnes ha^{-1})	Production (Tonnes ha^{-1})	Production (Tonnes ha^{-1})	Production (Tonnes ha^{-1})	Production (m^{3}ha^{-1})
1	Crop	2.35E+11	3.420	7.620	-	1.620	-
2	ICL	2.06E+11	3.900	7.200	0.031	-	-
3	Livestock	4.63E+07	-	-	0.007	-	-
4	Livestock	7.81E+09	-	-	1.263	-	-
5	Livestock	4.54E+08	-	-	0.073	-	-
6	Livestock	1.72E+09	-	-	0.279	-	-
7	ICL	2.30E+11	4.020	8.220	0.504	-	-
8	Crop	1.77E+11	3.540	6.000	-	-	-
9	ICL	1.58E+11	3.000	5.400	0.293	-	-
10	Livestock	8.54E+08	-	-	0.138	-	-
11	Crop	1.85E+11	3.360	6.600	-	-	-
12	Crop	1.60E+11	3.600	5.040	-	-	-
13	Crop	1.90E+11	3.360	6.900	-	-	-
14	Crop	2.24E+11	4.680	7.380	-	-	-
15	Crop	1.92E+11	3.300	7.080	-	-	-
16	Livestock	6.87E+08	-	-	0.111	-	-
17	ICL	2.13E+11	4.020	7.260	0.683	-	-
18	Livestock	4.79E+08	-	-	0.078	-	-
19	ILF	9.46E+10	-	-	0.390	-	6.080
20	Crop	1.85E+11	3.480	6.480	-	-	-
21	Crop	1.78E+11	3.582	6.000	-	-	-
22	Crop	2.20E+11	4.080	7.800	-	-	-

Table 4.3: Production

The integrated system, also, can boost crop productivity. Previous studies in Cerrado indicated that these systems can improve soil fertility over time and be more productive than the continuous soybean-corn systems (dos Reis et al., 2019; Macedo, 2009; Salton et al., 2014; Vilela et al., 2011). Nonetheless, the productive improvement is not so significant than that observed in the livestock farms. On the other hand, the major impact of the integrated systems on crop production is diminishing the cost production being more efficient in productive resource use and less dependent of external input (dos Reis et al., 2019). Our results for fertilizers and pesticides use showed the crop system heavy dependence on these inputs, but its productivity was quite similar than the integrated system farms (Table 4.3). Therefore, the integrated system can be an alternative to maintain high productivity in crop production, boost efficiency in natural resource use and, at the same time, improve the Brazilian competitiveness on global market.

4.4.2- The challenges of the cattle ranches

Livestock is one of the main drivers for deforestation in the Amazon (Barona et al., 2010; Lapola et al., 2014; Margulis, 2004). If, over the time, the strategy to maintain the economic results was increasing pasture areas intensifying pressure on natural forest, this practice has declining because the strengthening of social pressure and anti-deforestation legislation (Brasil, 2012b; Nolte et al., 2017, 2013). The poor profit results for livestock reduce its competitiveness and explain the general picture provides in (Figure 4.1). Crop production occupying the areas already used for agriculture in which large-scale production is viable, and livestock has being moved to frontier regions (Barona et al., 2010; Macedo et al., 2012).

Increasing the economic returns is decisive for livestock. Improve technological level adopting pasture management practices is a key issue for boost productivity and reduce livestock negative environmental impacts (Gil et al., 2018; Strassburg et al., 2014; zu Ermgassen et al., 2018). Traditional livestock systems, i.e. farms number #3, #5, #10 and #18 illustrate the huge challenge for cattle ranchers. These farms showed the lowest production level and the highest GHG emission results (Table 4.1 and 4.3). Furthermore, the cattle ranchers have limited financial capacity to implement new and more expensive practices and, as results indicated, they present high debt level. Therefore, public policies to enhance high technology adoption associated with specific credit support are crucial for improving livestock performance in Cerrado and the

Amazon region.

On the other hand, it is essential consider that farms number #3 and #5 are located at Pantanal biome, which impose a set of different issues to evaluate their sustainable performance. A promising example, also using Fuzzy logic approach, is the work proposed by Santos et al. (2017). Extensive livestock is a traditional activity in Pantanal (Abreu et al., 2010) and its population, known as Pantaneiros, has origins in indigenous groups in the region (Rossetto and Girardi, 2015; Schulz et al., 2019) showing intrinsic relationship and intimate knowledge of nature, as well as about their distinctive flooding regime characterized by a "flood pulse" (Junk and Cunha, 2005). Moreover, livestock activity in Pantanal arising from ancestral practices, shaping material and immaterial aspects of Pantaneiro's culture (Dalla Nora and Rossetto, 2015; Rossetto and Girardi, 2015; Schulz et al., 2019) and involving the management of the cattle on large natural pastures (Abreu et al., 2010) which provides a set of ecosystem service as control of burned on pastures in dry season and reduction of available biomass to decompose during the flooding season minimizing carbon emission (Bergier et al., 2019; Santos et al., 2017)

Hence, cattle ranchers in Pantanal, besides the general incentives indicated above, need specific consideration to improve their economic performance without compromise their culture and their ancestral connection with the Pantanal environment. Livestock intensification strategies should encompass the specificities of this biome, their population, the connection between livestock activity and their culture and include innovative instruments as payments for environmental services (Schulz et al., 2019, 2015) or some market differentiation as certification (Bergier et al., 2019). Furthermore, it is crucial associate high productivity practices with specific production conditions as natural pastures usage and the singular hydrological pattern of Pantanal, and it is imperative include farmer's participation in conceiving and implementation of public policies in the region.

4.4.3- CLF and Brazilian Government International agreements

Our findings suggest that the Brazilian government focuses on encourage adoption of the integrated systems can be an effective strategy to promote sustainable agriculture in Cerrado and the Amazon. Spite of has presented lower profit values, the integrated systems displayed economic results as good as the large-scale crop farms. Moreover, they presented higher social results in job quality, schooling and family labor, and notable environmental performance in fertilizer usage, topsoil loss, and, particularly, in GHG emissions and % forest, a relevant driver do reduce biodiversity loss (Benton et al., 2003; Perfecto and Vandermeer, 2010).

Considering that the area allocated to these systems in Brazil was around 11.5 million hectares in 2015/2016 (Embrapa; Rede ILPF, 2017), which represents 3.2% of agriculture area in Brazil (Instituto Brasileiro de Geografia e Estatística, 2020), the potential contribution of the integrated systems for Brazil achieves a massive reduction in GHG agriculture emission is substantial. Only in Mato Grosso, the potential reduction in 2017/2018 season for integrated system adoption was about 3.8 million tCO2eq (dos Reis et al., 2020).

Furthermore, the contribution of the integrated systems to reduce deforestation is also remarkable (Herrero et al., 2010; Lemaire et al., 2014; Vilela et al., 2011). For the season 2017/2018, the area allocated in Mato Grosso for crops was 9.5 million hectares, for livestock 23.03 million hectares (IMEA, 2020) and for integrated systems was 1.8 - 2 million hectares (dos Reis et al., 2020). If, all beef cattle production in this season was carried out only in livestock farms, the pastures area would be 388.000 hectares higher. The land saving for soybean production for 2017/2018 season was 79.000 hectares (dos Reis et al., 2020). In the present context of increasing deforestation rates in the Amazon region (INPE, 2020), and its impacts on climate change and biodiversity loss, the land saving potential of the integrated system assumes worldwide interest.

4.4.4- Sustainability as balance use of resource and continuity over time

The overall sustainability index highlights the presumption that sustainability is associated with balance interrelationship across economic, social and environmental dimensions (Graziano da Silva, 2010; Mebratu, 1998; Munasinghe, 1995; Sachs, 1986; Veiga, 2008) and that sustainable agriculture systems preserve the productivity capacity of environmental resources ensuring its continuity over time (Foley et al., 2011; Godfray et al., 2010; Hansen, 1996; Herrero et al., 2010; Smit and Smithers, 1993).

The crop systems showed high productivity and high economic performance. However, these results are based on excessive use of fertilizers and pesticides. In addition, the values for topsoil loss and, particularly, for runoff evidence the negative impact of continuous large-scale crop system on soil, harming the continuity of this system over time (Anache et al., 2017; Rieger et al., 2016). To maintain high productive levels, crop farms consumption of external inputs tend to be constantly high. As a result, to deal with increasing cost production, crop farms need to become bigger to take advantage of scale returns. This pattern illustrates the unsustainability of the high technological crop farms in the long run.

On the other hand, the top ranking values for the integrated systems are explained by balance interaction across all dimensions (Herrero et al., 2010; Lemaire et al., 2014; Reis et al., 2016; Salton et al., 2014). The economic results for profit, debit level and salary are closely related with lower cost production due to the high efficiency on input use. This efficiency explains the higher environmental performance. Furthermore, the positive environmental impacts on natural resources, particularly in GHG emission, % forest and soil, ensure the productive conditions for the integrated systems continue over time and are one reason for the results for farm values. Finally, the result for "training and courses" confirms the perspective that the integrated systems demand more qualified workers and offer higher quality job, which is determined by higher salaries and social insurance. The harmonious interaction of economic, environmental and social components generates a continuous and sustainable trajectory.

4.5- Final remarks

Finding alternatives to deal with the global social problem of the increasing demand for food and, simultaneously, preserving the environmental resource is crucial for agriculture sector. The negative environmental impacts of the large-scale agriculture and the traditional livestock compromise the continuity of these productive systems in the long-run. Our results indicated that the integrated systems can be considered a viable option of current agricultural activities. The multiplicity of configurations of the integrated systems makes possible to use this technology for any type of producer, regardless of size, region, product or any other structural feature that should be considered for setting the productive structure.

However, the adoption rate of the integrated systems in Brazil is low, only 3.2% of the area allocated for agriculture. In addition of public policies to strengthen the research, the Brazilian government needs to implement specific actions to boost the adoption, such as: i) simplifying credit access; ii) expanding transfer technology programs; and iii) improving rural assistance. Social and cultural barriers are another important issue. Therefore, increasing the number of demonstrative unities as well as widening availability of research results can influence farmer's decision.

Finally, the fuzzy inference model proposed provides a practical tool to assess sustainability. However, bearing in mind the impossibility for understand and incorporate all sustainability issues, the proposed model is inherently dynamic and its development process is continuous, making possible to include expert's knowledge improvements and changes in sociopolitical objectives of decision makers.

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4.6- Supplementary Information

4.6.1- Fuzzy inference Sets and Fuzzy inference Rules

For each economic, environmental and social (EES) variable were attributed five linguistic variables:

- Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH)

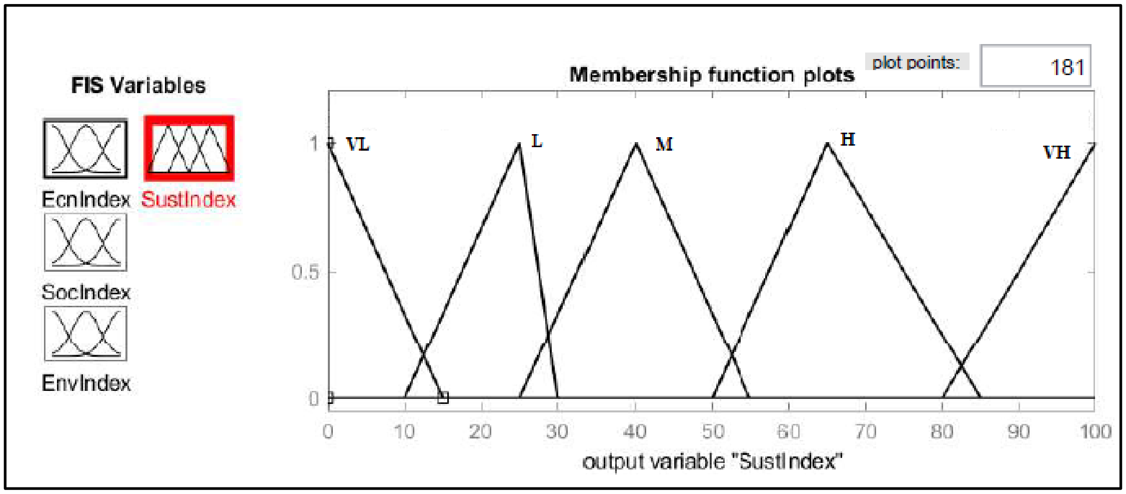
Each dimension has 6 inputs variable, see (Table 4.1, main text).

The total possible combinations is defined by an exponential formula: X^y; where (X) is de number of linguistic variable and (y) is the number of inputs (6). The combination of all of then generated:

- 16625 combinations for economic set;
- 3125 combinations for social set since two inputs (Health Plan, and Profit Share are dichotomous variable (yes or no);
- 15625 combinations for environmental set;
- 125 combinations for the overall sustainability index

The attribution of linguistic values as well as the fuzzy rules formulation was are built based on experts' knowledge (Cornelissen et al., 2003; de Vos et al., 2013; Liu, 2007; Zadeh, 1989), in a recursive process to achieve a better setting for the available information set.

Representation of the membership function for the overall sustainability index:



Source: MATLAB Fuzzy Logic Toolbox

The table below displays, as example of a Fuzzy rule set considering the IF- THEN proposition, the fuzzy rules for the overall sustainability index:

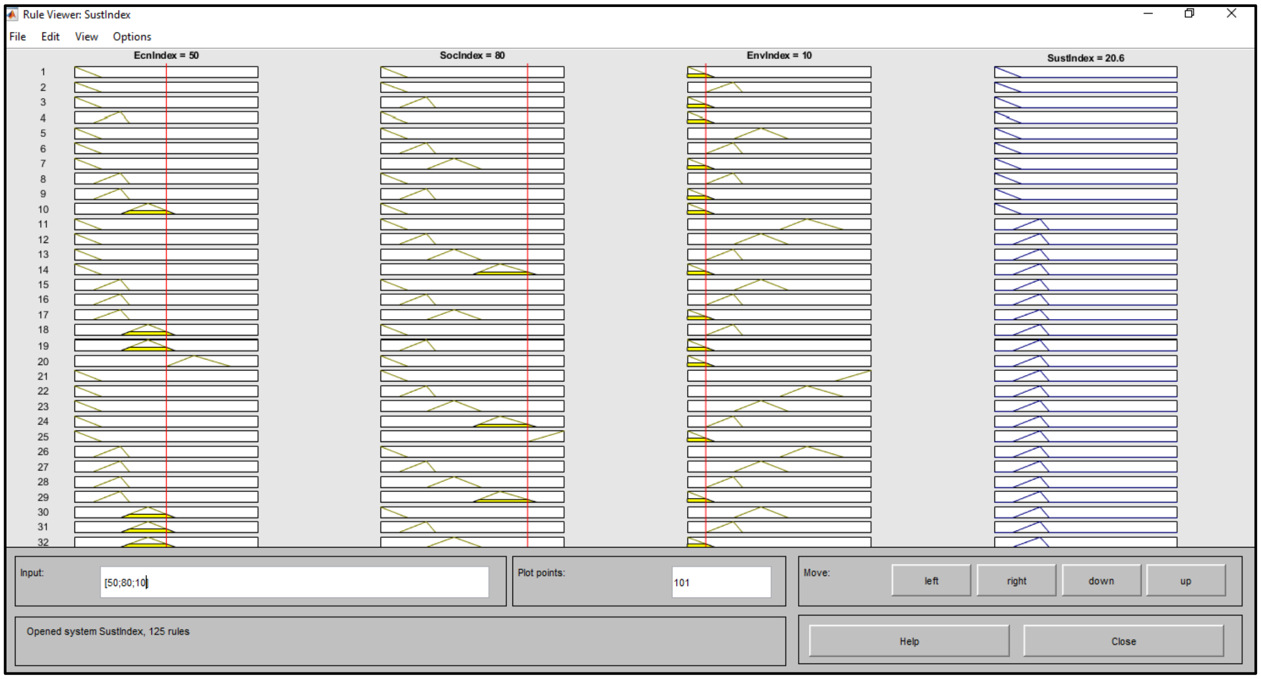
If Economic	and Social	and Environmental	Then Sustainability Index
VL	VL	VL	**VL**
VL	VL	L	**VL**
VL	L	VL	**VL**
L	VL	VL	**VL**
VL	VL	M	**VL**
VL	L	L	**VL**
VL	M	VL	**VL**
L	VL	L	**VL**
L	L	VL	**VL**
M	VL	VL	**VL**
VL	VL	H	**L**
VL	L	M	**L**
VL	M	L	**L**
VL	H	VL	**L**
L	VL	M	**L**
L	L	L	**L**
L	M	VL	**L**
M	VL	L	**L**
M	L	VL	**L**
H	VL	VL	**L**
VL	VL	VH	**L**
VL	L	H	**L**
VL	M	M	**L**
VL	H	L	**L**
VL	VH	VL	**L**
L	VL	H	**L**
L	L	M	**L**
L	M	L	**L**
L	H	VL	**L**
M	VL	M	**L**
M	L	L	**L**
M	M	VL	**L**
H	VL	L	**L**
H	L	VL	**L**
VH	VL	VL	**L**
VL	L	VH	**L**
VL	M	H	**L**
VL	H	M	**L**
VL	VH	L	**L**
L	VL	VH	**L**
L	L	H	**L**
L	M	M	**L**
L	H	L	**L**

L	VH	VL	**L**
M	VL	H	**L**
M	L	M	**L**
M	M	L	**L**
M	H	VL	**L**
H	VL	M	**L**
H	L	L	**L**
H	M	VL	**L**
VH	VL	L	**L**
VH	L	VL	**L**
VL	M	VH	**M**
VL	H	H	**M**
VL	VH	M	**M**
L	L	VH	**M**
L	M	H	**M**
L	H	M	**M**
L	VH	L	**M**
M	VL	VH	**M**
M	L	H	**M**
M	M	M	**M**
M	H	L	**M**
M	VH	VL	**M**
H	VL	H	**M**
H	L	M	**M**
H	M	L	**M**
H	H	VL	**M**
VH	VL	M	**M**
VH	L	L	**M**
VH	M	VL	**M**
VL	H	VH	**M**
VL	VH	H	**M**
L	M	VH	**M**
L	H	H	**M**
L	VH	M	**M**
M	L	VH	**M**
M	M	H	**M**
M	H	M	**M**
M	VH	L	**M**
H	VL	VH	**M**
H	L	H	**M**
H	M	M	**M**
H	H	L	**M**
H	VH	VL	**M**
VH	VL	H	**M**
VH	L	M	**M**
VH	M	L	**M**

VH	H	VL	**M**
VL	VH	VH	**H**
L	H	VH	**H**
L	VH	H	**H**
M	M	VH	**H**
M	H	H	**H**
M	VH	M	**H**
H	L	VH	**H**
H	M	H	**H**
H	H	M	**H**
H	VH	L	**H**
VH	VL	VH	**H**
VH	L	H	**H**
VH	M	M	**H**
VH	H	L	**H**
VH	VH	VL	**H**
L	VH	VH	**H**
M	H	VH	**H**
M	VH	H	**H**
H	M	VH	**H**
H	H	H	**H**
H	VH	M	**H**
VH	L	VH	**H**
VH	M	H	**H**
VH	H	M	**H**
VH	VH	L	**H**
M	VH	VH	**VH**
H	H	VH	**VH**
H	VH	H	**VH**
VH	M	VH	**VH**
VH	H	H	**VH**
VH	VH	M	**VH**
H	VH	VH	**VH**
VH	H	VH	**VH**
VH	VH	H	**VH**
VH	VH	VH	**VH**

The figures below show an example of the Fuzzy inference system and the deffuzification process for the input set:

- [economic indicator (50); social indicator (80) and environmental indicator (10]
- The overall sustainability index final result was 20.6



EcnIndex = 50

SocIndex = 80

EnvIndex = 10

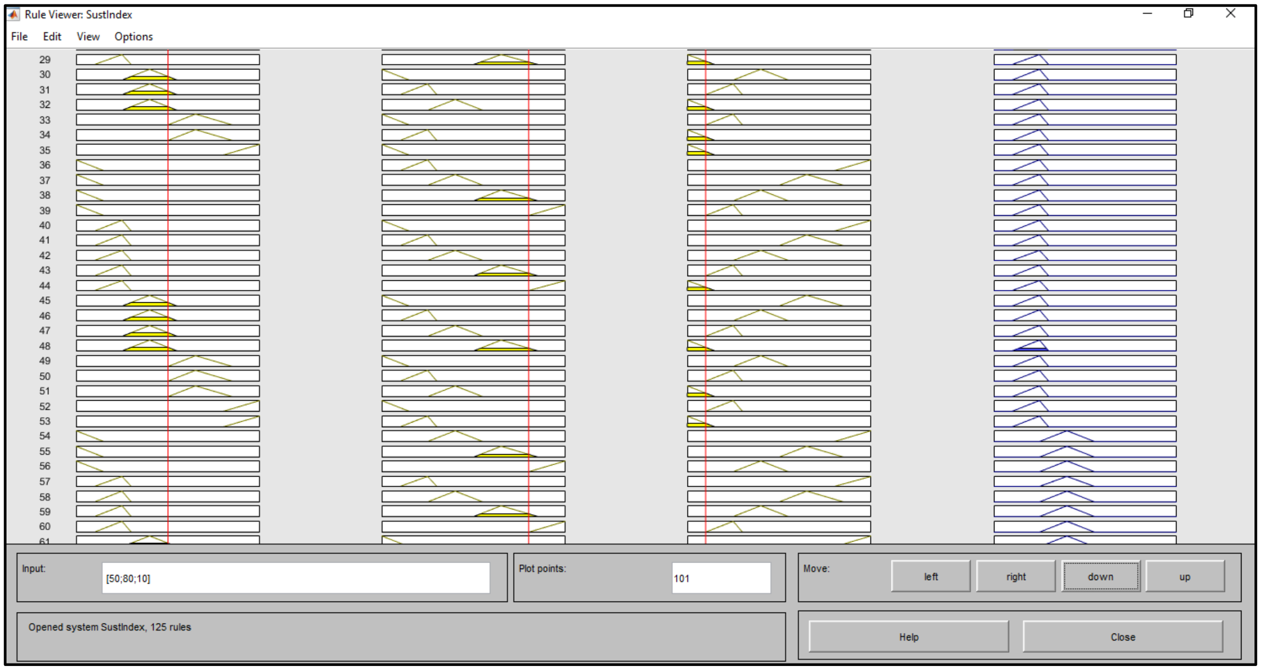
SustIndex = 20.6

Input: [50;80;10]

Plot points: 101

Opened system SustIndex, 125 rules

Source: MATLAB Fuzzy Logic Toolbox

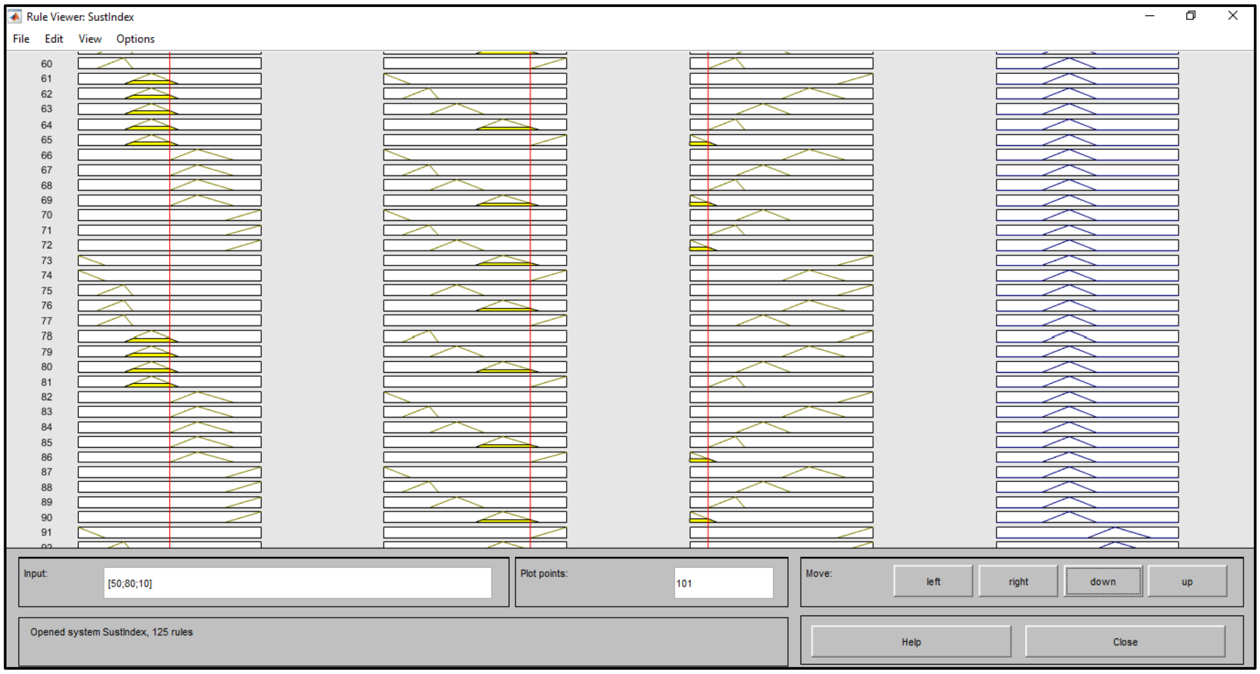


Input: [50;80;10]

Plot points: 101

Opened system SustIndex, 125 rules

Source: MATLAB Fuzzy Logic Toolbox

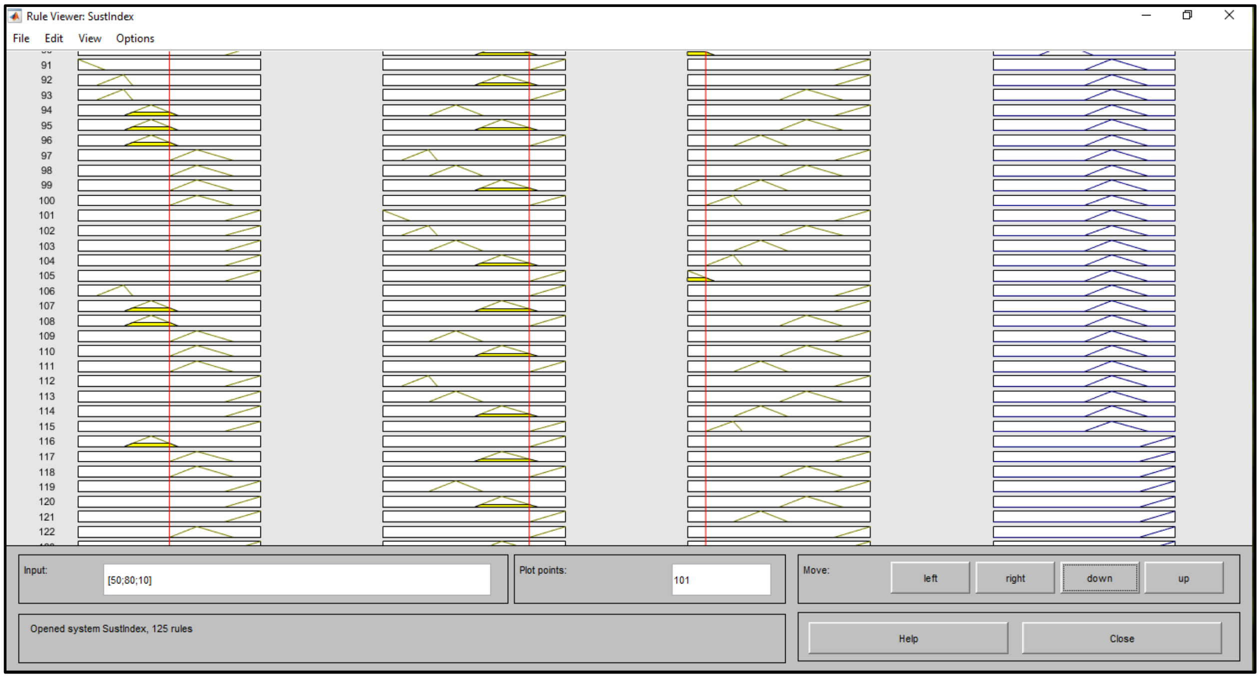


Input: [50;80;10]

Plot points: 101

Opened system SustIndex, 125 rules

Source: MATLAB Fuzzy Logic Toolbox

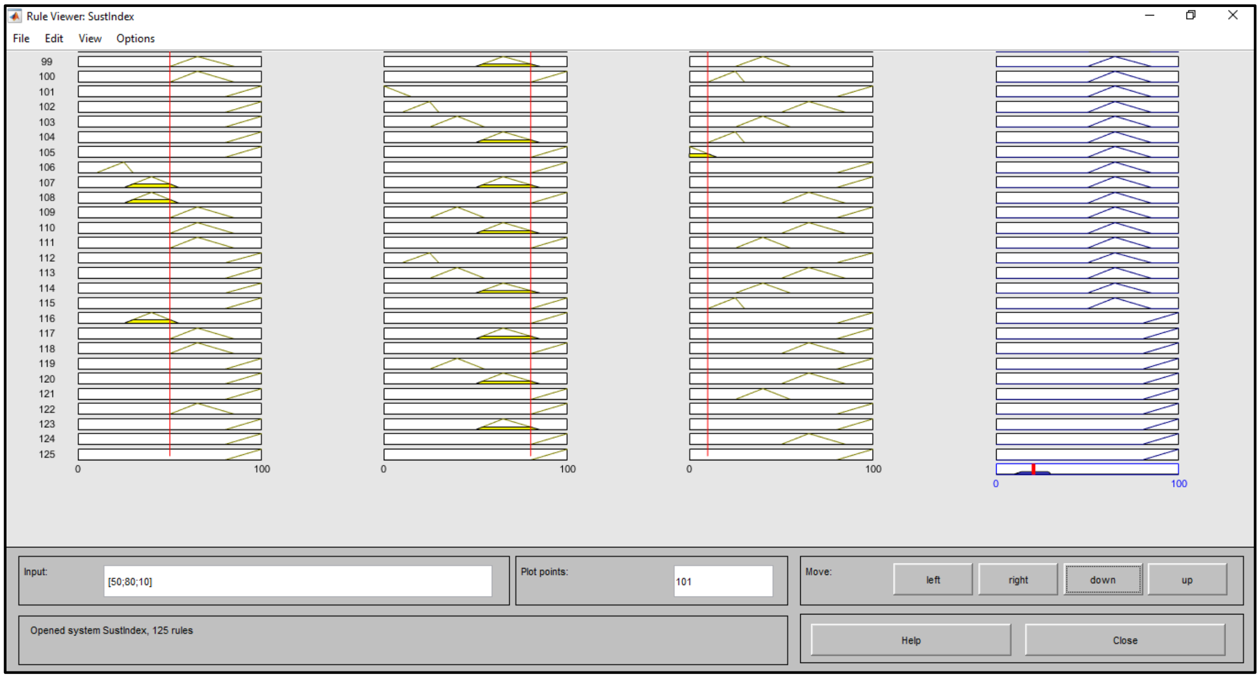


Input: [50;80;10]

Plot points: 101

Opened system SustIndex, 125 rules

Source: MATLAB Fuzzy Logic Toolbox



Input: [50;80;10]

Plot points: 101

Opened system SustIndex, 125 rules

Source: MATLAB Fuzzy Logic Toolbox

4.6.2- Indicators Set Guideline

Variable	Dimension	Definition	Expected effect
Profit (P)	Economic	General measure of economic performance	$If\,(P)\uparrow\Rightarrow(SI)\uparrow$
Debit level (DL)	Economic	% of debit in current expenses per hectare discounted by the period that the farmer adopts the productive system	$If\,(DL)\uparrow\Rightarrow(SI)\downarrow$
Difference of Salary (DS)	Economic	Ratio: salary paid to decision maker in the farm and the average salary in Mato Grosso	$If\,(DS)\uparrow\Rightarrow(SI)\uparrow$
Production (Pr)	Economic	Total production converted in energy (J)	$If\,(\mathrm{Pr})\uparrow\Rightarrow(SI)\uparrow$
Farm Value (FV)	Economic	Monetary value of farm (ha^{-1}) discounted by the period that the farmer adopts the productive system	$If\,(FV)\uparrow\Rightarrow(SI)\uparrow$
Fuel Comsuption (Fu)	Economic	Ratio: fuel consumption (ha^{-1}) and total produced energy (J)	$If\,(Fu)\uparrow\Rightarrow(SI)\downarrow$
Schooling (S)	Social	Farmr's years of study	$If\,(S)\uparrow\Rightarrow(SI)\uparrow$
Family labour (Fl)	Social	Ratio: age of younger family's member working on farm and age of elder	$If\,(Fl)\uparrow\Rightarrow(SI)\downarrow$
Training and Courses (TC)	Social	Number of training and courses	$If\,(TC)\uparrow\Rightarrow(SI)\uparrow$
Job Quality (JC)	Social	Ratio: (permanent employee + temporary employee)/temporary employee	$If\,(JC)\uparrow\Rightarrow(SI)\uparrow$
Health Plan (HP)	Social	Farm provides health plan for employees (yes or no)	$If\,(HP)\uparrow\Rightarrow(SI)\uparrow$
Profit Share (PS)	Social	Farm provides profit share (yes or no)	$If\,(PS)\uparrow\Rightarrow(SI)\uparrow$
Topsoil loss (TL)	Environment	Ratio: amount of topsoil loss (kg ha^{-1}) and total produced energy (J)	$If\,(TL)\uparrow\Rightarrow(SI)\downarrow$
Fertilizers (Fe)	Environment	Ratio: amount of fertilizers (kg ha^{-1}) and total produced energy (J)	$If\,(Fe)\uparrow\Rightarrow(SI)\downarrow$
Pesticides (P)	Environment	Ratio: amount of pesticides (active ingredient) (kg ha^{-1}) and total produced energy (J)	$If\,(P)\uparrow\Rightarrow(SI)\downarrow$
% Forest (Fo)	Environment	Difference between the % forest preserved on farm and the % indicated in legislation (Brazilian Forest Code)	$If\,(Fo)\uparrow\Rightarrow(SI)\downarrow$
GHG emission (GHG)	Environment	Ratio: tonnes CO_{2eq} and total produced energy (J)	$If\,(GHG)\uparrow\Rightarrow(SI)\downarrow$
Runoff (R)	Environment	(precipitation – evapotranspiration)/precipitation	$If\,(R)\uparrow\Rightarrow(SI)\downarrow$

CHAPTER 5

FINAL CONSIDERATIONS

5- FINAL CONSIDERATIONS

The crop-livestock (ICL) and the crop-livestock-forest (ICLF) systems are a Brazilian technology for enhancing Brazilian agricultural productivity and, simultaneously, reducing agriculture negative impacts on the environment. Over the three chapters presented above, we provide an innovative comprehensive applied analysis to evaluate agricultural systems performance in Mato Grosso, and to compare the integrated systems results with large-scale crop systems (continuous soybean-corn system) and continuous extensive livestock system situated in the main agricultural productive Brazilian region.

The comprehensive analysis of the integrated systems sustainability in comparison with typical large-scale continuous crop systems and with typical continuous livestock systems highlights the superior performance of those systems. These findings are extremely relevant for policy makers, since they illustrate how important is taking into account the long-run performance of agricultural systems to build effective strategy to promote sustainable development.

The results showed in chapter 2 and 3 illustrate the attractive economic return of large-scale continuous crop systems and indicate that in a scenario of high commodity prices, these production systems present the best economic performance. Therefore, for those who consider the economic results the most relevant issue to take decisions about what productive system they should adopt, the typical large-scale continuous crop system tends to continue the best option, under a favorable global market. However, this option is fundamentally dependent of market conditions and, thus can generate high returns or huge losses, depending on market prices.

On the other hand, the emergy analysis provided in the chapter 3 highlights the inherent contradiction of analyzing only the economic dimension of agricultural production, if we are focused on evaluating how agriculture sector can contribute for sustainable development. The emergy analysis, and its main assumption about the relevance of considering the work accomplished by the environment at the same basis than that work carried out in the economic subsystem, evidences that the social cost of large-scale continuous crop systems is higher than the social benefits provided for them. The crop systems are highly productive, but this performance relies on an intensive use of external inputs. As a consequence, they impose high stress on the environment making unsustainable their reproduction in the long-run.

Furthermore, both chapters show the potential for the integrated systems to be used as an efficient alternative for large-scale continuous crop systems. The economic analysis provided in chapter 2 evidences that the integrated system performs better than continuous crop-system in a scenario of low commodity prices level and in situation with high interest rates, even in regions highly specialized in crop production such as the Mid-North region of Mato Grosso. Moreover, the results confirm that the integrated systems present lower market risk level. In addition, the emergy analysis on chapter 3 demonstrates that the integrated systems presents a balance performance between resource use and productivity, are an effective strategy for land sparing, and can, effectively, contribute with reduction of GHG emission on agriculture sector since they are less dependent of external inputs. Also, the lesser dependency of external input can offer a real possibility, mainly for crop farmers, to release themselves from multinational companies control and their technological package. A few number of multinational companies control all commodities production chain, as well as the commercialization chain. Even big farmers are heavy dependent of external inputs, technological assistance and commercialization facilities provided by multinational companies. The integrated systems can be used as a national technology to enlarge the on-farm farmer’s decision power over their productive activity.

These findings, associated with the numbers of the integrated systems adoption in Brazil over the last years, suggest that the policy makers need to include instruments and information for changing farmer’s perceptions about the economic results provided by agricultural sector to booster integrated systems adoption. Even being a general perception, from an individual point of view, the environmental performance by the large-scale continuous crop systems demonstrated by the emergy analysis are not considered in the farmer’s decision.

There are important economic and social barriers that need to be considered to implement a transition for a more sustainable, but more complex, agricultural system such as the ICL and ICLF systems. In general, farmers are risk averse and perceive high upfront investment as an important barrier to implement the integrated system (Cortner et al., 2019; R. Garrett et al., 2017). The results showed in chapter 2 suggest that even requiring higher investment, the integrated system provides higher economic return and shorter economic risk. However, to achieve these results, farmers need to deal with growing management and operational challenges, and a considerable number of them, particularly cattle ranches, present strong resistance to adopt new and sophisticated technologies mainly if this process represent a growing indebtedness level. Moreover, cattle ranches demonstrate stronger cultural background and perceive adoption of the integrated system as a change in their familiar tradition (Cortner et al., 2019; R. Garrett et al., 2017; Skorupa and Manzatto, 2019).

Besides the on-farm issues, farmers have been indicated structural barriers to adopt the integrated systems such as difficulties obtaining qualified labor, absence of specialized technical assistance, limited information about integrated system performance and benefits, a lack of marketing options as price differentiation, bureaucracy to get loans available by ABC Plan, absence of policy for ecosystem service payments, and poor transportation and commercialization infrastructure (Cortner et al., 2019).

On the other hand, the survey carried ou by Embrapa and ICLF Network in 2017 revealed that the main aspect to encourage adoption of the integrated system is the adoption by a neighboring farmer (Embrapa; Rede ILPF, 2017). In addition, they highlight the important impact of technological demonstrative units as instrument to get specific information (Cortner et al., 2019; R. Garrett et al., 2017). These findings are critical issues to be included in public policy to encourage a transition to a sustainable agriculture trajectory in the Amazon and Cerrado regions. Indeed, Embrapa has been investing considerable effort in improve its technological demonstrative units network and is program of technology transfer (Skorupa and Manzatto, 2019). However, additional effort needs to be done to improve public extension to connect research to practice. While numerous research projects on ICLS currently exist in Brazil, the ability of agricultural experts to transfer this knowledge to farmers was perceived as very weak (R. Garrett et al., 2017).

Another important issue to encourage the adoption of the integrated systems is increasing restrictions on forest conservation for agriculture. Since the mid-2000s, efforts to improve enforcement of the Forest Code (Brasil, 2012b) and the implementation of zero-deforestation commitments by soy and cattle traders have acted to reduce land availability for agricultural expansion in the Amazon and encourage intensification on cattle farms (R. Garrett et al., 2017; Garrett et al., 2018; le Polain de Waroux et al., 2017).

Therefore, to boost adoption of the integrated systems, the Brazilian government needs to build public policies oriented to deal with micro and macro aspects. Moreover, these policies need to employ a more diverse set of policy tools beyond credit subsidies to encourage adoption of sustainable intensification strategies, including education programs, payments for the ecosystem services, and improved transportation and supply chain infrastructure that can support intensification and help create an environment of innovation (Cortner et al., 2019; dos Reis et al., 2020; R. Garrett et al., 2017; Garrett et al., 2020; Reis et al., 2016).

Furthermore, chapters 2 and 3 evidence the difficulties faced by cattle ranchers. Typical livestock systems present low economic return and the worst environmental performance. The emergy analysis highlights the lower efficiency of the typical continuous livestock to convert available resource in production. Moreover, these results demonstrate the heavy contribution of the livestock to GHG emission on agriculture sector.

Our finding reinforces the perception that typical cattle ranchers need substantial assistance to continue they activity. Not only financial assistance, but a set of public policies is need for tradition cattle ranchers overcome barriers such as: increase technological level, improve management practices, enhance commercialization strategies and, fundamentally, change they productive culture in order to associate economic results with reduction of negative environmental impact of livestock. The demand for beef cattle is rising worldwide. The key issue on this sector is meet demand with more efficient productive practices. In this context, our results demonstrated that beef cattle production in the integrated system were much more efficient. There is a remarkable productivity difference between the two productive systems and this difference is expressed on the economic and, particularly, on the environmental performance of the integrated systems as showed by emergy indicators in the chapter 3 and by fuzzy indicators in chapter 4.

As a synthesis of the findings on previous chapters, the chapter 4 expands the sustainability analysis of the agricultural systems in Mato Grosso gathering information from 22 different farms spread across the three biomes - Amazon, Cerrado and Pantanal -, existing in this state. The Fuzzy Set approach offers a comprehensive framework to generate sustainability indicators and, particularly, to connect the sustainability dimensions – economic, social and environmental – in a suitable and simplified panel of indicators to evaluate the contribution of each input to sustainability of the overall system.

The results showed in chapter 4, based on survey from real farms, reinforce the results displayed in previous chapters which were built based on case study data. Using the Fuzzy Set approach was possible consider the interrelationship across all available information, and generate a ranking considering sustainability performance. The final result, showed by the overall sustainability index, illustrated the superior performance of the integrated systems. All integrated systems farms showed very high or high sustainability level.

The striking SI result for the farm number #19, an integrated livestock-forest system, is due to its high specialization in teak production to international market combined with high technologic livestock practices. This farm presents intermediate economic result. However, its high organization and expertise in teak production explain its high social and environmental results. The efficiency in fertilizers and pesticides use and the ecosystem services provides by forest as low topsoil loss, sequestration of GHG and runoff mitigation explain its impressive environmental result and, as a result, it’s very high overall sustainability index.

The notable environmental performance provided by the forest highlights the relevance of this component to strengthen sustainability potential of the integrated systems. Our sample configuration, even does not having inference objectives, is a realistic representation of the integrated systems adoption pattern: 83% of integrated systems in Brazil are ICL, 9% are ICLF, 7% are ILF, and only 1% are ICF (Embrapa; Rede ILPF, 2017). The modest share of the forest component illustrates farmer’s perception about the management, operational and, particularly, commercial challenges facing with the forest component. Therefore, to boost forest component share, besides research and technological transfer initiatives, it is crucial building public policies focused on: to identify niche market for planted wood, to implement payments for ecosystem services programs, and, simultaneously, to improve enforcement of the deforestation policies. Moreover, it is imperative for policy makers take into account the positive contribution of diversified agriculture systems to biodiversity conservation by increasing matrix permeability and improving connectivity and heterogeneity of agricultural landscapes, mainly considering inclusion of forest component (Altieri, 1999; Donald and Evans, 2006; Goulart et al., 2013; Perfecto and Vandermeer, 2010), and provide monetary incentives for farmers who implement forest component.

Furthermore, this comprehensive approach highlights the relevance of a balance performance across all dimensions to promote sustainability. The continuous crop systems farms showed high economic performance, mainly for profit and production inputs, information strictly connect with traditional economic evaluation as that carried out in chapter 2. However, their environment results, mainly, for soil loss, external inputs usage, and runoff, evidence the unsustainable pattern of large-scale continuous crop systems.

In addition, as observed previously, the typical livestock systems presented the poorest performance. Even high technological livestock farms showed low sustainability level, particularly, because their bad environmental performance. The association of the economic, social and environmental aspects provided by the Fuzzy Set approach and the general picture provided by the partial and overall sustainability index emphasized the unsustainable pattern of current livestock production in the Amazon and Cerrado regions.

Moreover, the results provided by the overall sustainability index illustrate the relationship between the scale of production of agriculture in Mato Grosso and its environmental results. The economic variable set used expresses the scale of production considering information about production and productivity, debit level, profit and farm value, and the environment variable set indicates the pressure on the natural resources and on the services provided for the natural capital taking into account information of pesticides, fertilizers, GHG emission and top soil loss. The SI index highlights that the integrated systems exert less pressure on the environment and present better economic and social results. Future researches should expand the variable set, improving information from environmental variables to detail the impact of scale of production on nutrient cycles and, as consequence, advancing knowledge about the resilience of the environment, the magnitude of agricultural pressure on biogeochemical cycles and, as a result, enhance our comprehension abou the contribution of agriculture for the sustainable development.

Finally, this research displays results to support the assumption that the integrated systems are a successful strategy for Brazil reinforces its position as a key player in the global food market. Furthermore, our findings confirm that Brazilian government commitments in increasing integrated systems area can be an efficient public policy to implement a sustainable land use in the Amazon and Cerrado regions, and, as a consequence, an effective strategy to reduce the agricultural negative impacts on climate change. In addition, this research provides three analytical instruments to evaluate and to compare agricultural systems performance. In order to improve general knowledge about sustainability of agriculture sector in the Amazon and Cerrado, widespread application of those instruments in a large sample might be an interesting and relevant research agenda to continue this work.

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7- APPENDIX

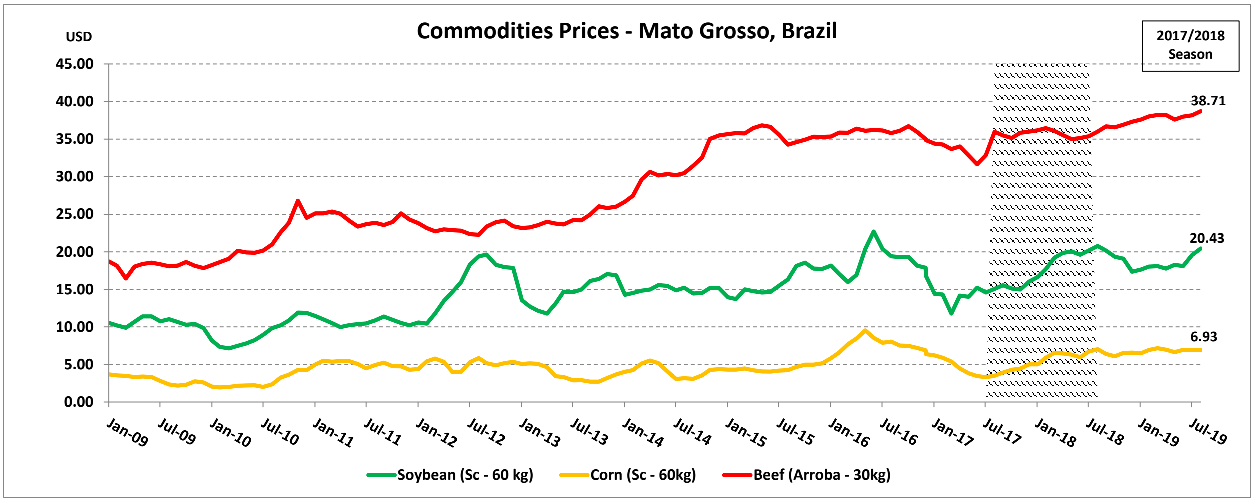
Appendix 1 – Summary Literature Review: Economic analysis of integrated crop and livestock systems in Brazil

Authors	Focus of the analysis	Productive Systems	Period	Indicators	Main results
(Muniz et al., 2007)	Economic viability and minimizing market risks	iCL in Goias, Brazil	3 years, using simulations	NPV and IRR	The iCL was economically viable in all scenarios considered
(Lazzarotto et al., 2010)	Economic viability and minimizing market risks	iCL, continuous crop system (soybeans and corn in the summer and wheat in the winter) and continuous livestock (beef cattle) system in Paraná, Brazil	13 years, using simulations	NPV and IRR	In both situations (real and simulated) the iCL presented better economic results: NPV 103% higher than the crop system and 19.6% higher than the livestock system. Furthermore, the iCL presented lower probabilities to displays negative NPV considering investment and prices fluctuations
(Oliveira et al., 2014)	Economic viability	iCL and continuous crop system (soybean) in Rio Grande do Sul, Brazil	12 years	Productivity and Gross Margin	The iCL presented better results, especially in years when the rainfall volume in crop development time was insufficient
(Costa et al., 2012)	Economic viability, cash	iCL; iCLF with eucalyptus trees on simple	12 years, with real data for	NPV	The lower necessity of investing on the iCL to both iCLF in addition to a return

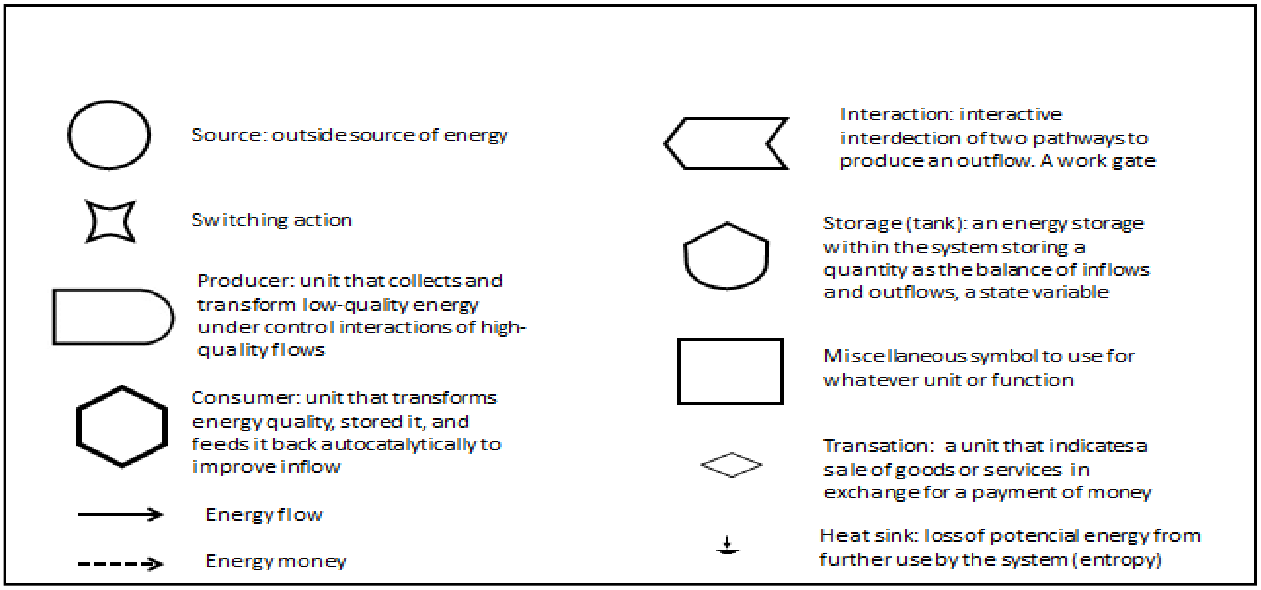
	flows dynamics and higher investment requirements	lines (227 trees/ha) and iCLF with eucalyptus on simple lines (357 trees/ha), in Mato Grosso do Sul, Brazil	the first two years		on capital invested in a shorter period, indicate that system iCL tends to be a more suitable alternative to producers who deals with financial constraints and/or risk averse.
(Martha Júnior et al., 2011)	Economic viability	iCL; continuous livestock system (beef cattle) and an continuous crop system (soybean) in Goias, Brazil	1 year	Net Revenue, Productivity and Entrepreneur Return Rate	The iCL was more economic attractive than the livestock system, but did not show better results than the soybean crop system. The ERR for the livestock system was negative (-1.55%), for the iCL the return rate was 26.7% and 55.9% for the soybean crop system
(De Oliveira et al., 2013)	Economic viability	iCLF system in Goiás, Brazil	7 years, with real data for the first three years	NPV and IRR	Due to favorable crop prices scenario, the economic results were very positive: NPV annual of USD 269.53 ha to 2009 prices. For the IRR the value was 54.24%, well above the attractiveness minimum rate considered, which was 8.75%.

* iCL = Integrated Crop and Livestock system
iCLF = Integrated Crop, Livestock and Forest system
NPV = Net Present Value
IRR = Internal Return Rate
ERR = Entrepreneur Return Rat

Appendix 2: Commodities Prices – Mato Grosso, Brazil 2009-2019



Appendix 3: Symbols meaning Emergy flows diagrams



Source: outside source of energy

Switching action

Producer: unit that collects and transform low-quality energy under control interactions of high-quality flows

Consumer: unit that transforms energy quality, stored it, and feeds it back autocatalytically to improve inflow

Energy flow

Energy money

Interaction: interactive interdection of two pathways to produce an outflow. A work gate

Storage (tank): an energy storage within the system storing a quantity as the balance of inflows and outflows, a state variable

Miscellaneous symbol to use for whatever unit or function

Transation: a unit that indicates a sale of goods or services in exchange for a payment of money

Heat sink: loss of potencial energy from further use by the system (entropy)