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Emergy accounting as a support for a strategic planning towards a regional sustainable milk production

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ABSTRACT

Milk is one of the most important food in the world, being consumed *in natura* or supporting the dairy industry. In Brazil, specifically, the milk supply chain corresponds to about 20% of its agro-industrial gross domestic product; however, the productivity of most domestic milk production systems are still characterized as low. In view of this, the Brazilian government supports training programs to increase milk productivity and economic returns, however, sustainability issues are usually left in the background. This work uses emergy environmental accounting to study the sustainability of milk production systems in the southern region of Minas Gerais state, Brazil, aiming at two specific goals: (i) verifying their individual environmental performance based on emergy indices, and (ii) exploring alternatives for the development of milk production under a regional perspective. Results from a cluster analysis evidenced the existence of five main milk production systems in the region (G1–G5), including differences in productivity, handling, feed diet, infrastructure, and administrative control. Emergy indicators point to the G3 system (small-scale, family-managed) as the best performer concerning renewability (28%), yield (EYR 1.72), investment (EIR 1.39), environmental load (ELR 2.46), and sustainability (ESI 0.70); however, the G2 system should be promoted when equally considering ESI and efficiency for a decision. Under a regional perspective, increasing milk productivity will also increase a system's dependence on fossil-based resources, which results in an uneven emergy matching and in a less efficient use of emergy. On the other hand, pursuing the increase of sustainability for milk production by optimizing the regional EIR would result in an expansion of the G3 system in 96% of all milking areas and the production would decrease by about 57%. Such trade-off claims for different policies in accordance with societal objectives in different periods. Besides diagnosing and ranking the milk production systems according to their environmental performance, this work also provides important subsidies for decision-makers regarding a strategic plan towards a sustainable milk production under a regional perspective.

1. Introduction

Brazil is among the largest cow milk producer nations in the world. According to FAO (2013), 5.3% from the world total is produced in Brazil, following China (6%), India (8.6%) and the United States (14.7%). With producing units scattered throughout the nation, the dairy industry employs over 3 million people throughout its supply chain, and accounts for approximately 20% of the nation's agribusiness GDP. The current 35 billion liters production, along with the aim to reach 41 billlion liters by 2023, make milk a hugely important product for the country, both socially and economically CEPEA, 2013).

According to IBGE (2013), approximately 75% of the Brazilian producers use the so-called extensive production systems, where the cattle feed is based on generally low-productivity pastures. Additionally, the animals feature a reduced genetic potential for milk production, thus resulting in low productivity rates, reaching as low as 730 L/cow.yr, in average (Zoccal and Carneiro, 2008). On the other side, intensified systems yield higher productivity, as a result of the use of technical knowledge and skills, special cattle, concentrated soy, maize, vitamins and minerals-based feed, along with a rigorous production accounting control; according to Maia et al. (2019), these systems represent a 3% of the total, however, their productivity can reach as much as 14,000 L/cow.yr. Between these two extremes lie the so-called intermediate producers. Data from IBGE (2013) point out that

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the intensification of milk production in Brazil, starting in the 1990's, resulted in an increase in average productivity, from 759 cow-yr in 1990 to 1471 L/cow-yr in 2013. Such result, however, is still low, when compared to those from the United States (9593 L/cow-yr), Spain (7497 L/cow-yr), Mexico (4541 L/cow-yr), and Argentina (4496 L/cow-yr), among others.

Minas Gerais is the largest milk producer in Brazil, with 27% of the overall national production, and the southern region of the state stands out with 11% of the state total (IBGE, 2013); additionally, this region shelters a huge diversity of milk producers, in terms of productivity and intensification, which represents the typical Brazilian production feature. The majority of the producers in this region are of the extensive type, and they are liable to join government-supported intensification-encouragement programs, such as the Minas Leite (Emater, 2014), or the Balde Cheio (Embrapa, 2014) programs, aimed at enhancing family-business producers' income from dairy-producing activities, thus preventing them from migrating to urban centers. Such programs aim at promoting producers' technical capacitation, which aids in cattle productivity and financial benefits (Affholder-Figuie and Bainville, 1998; Cardoso et al., 1999; Abdalla et al., 1999; White et al., 2002; Heikkilä et al., 2008; Leonelli, 2010). As a result, while securing higher production levels of such important foodstuff to humanity, these programs could motivate the small producers to stay in the countryside, thus avoiding a series of social issues that could result from a de-ruralization process (Weiss-Altaner, 1983; Weissteiner et al., 2011; Batista and Hespanhol, 2014).

Production intensification results in higher productivity, and, consequently, improvements in economic and social indicators (Heikkilä et al., 2008). However, some questions still lie unanswered, when considering a conceptual sustainability model that focuses on thermodynamics-based growth constraints (i.e., limited biophysical availability of resources). In this sense, some doubts are raised: what is the most sustainable milk production system, among the existing ones, in the southern region of Minas Gerais state? How to supply subsidies for decisors, regarding a regional planning for milk production?

Some studies in this regard were carried out, by considering the life cycle assessment or the carbon footprint in studying milk production systems (Casey and Holden, 2005; Rotz et al., 2010; Flysjö et al., 2011; Hagemann et al., 2011; Shortall and Barnes, 2013), nevertheless, works considering a donor side perspective under a more holistic perspective are hardly found. Odum (1996), however, argues that using emergy evaluation (spelled with an "m") as a scientific tool could show which environmental management pattern would maximize economic vitality with less trial and error, allowing society to increase production systems efficiency and be innovative with fewer failures and, as a result, adapt to changes more rapidly. Emergy accounting, therefore, appears as an effective complement in assessing the sustainability of production systems, as it considers a donor side perspective and the biosphere as a scale for the assessment, which allows it to account for all energy pathways supporting the production system. All energy flows from the natural environment and those from the larger economy are embodied in the final product or service. The use of emergy accounting is rapidly increasing in scientific studies due to its robustness (Giannetti et al., 2013a) and powerful sustainability assessment. Among other studies, emergy synthesis is being applied to assess environmental services (Campbell and Brown, 2012), agricultural production (Agostinho et al., 2008; Giannetti et al., 2011), buildings (Giannetti et al., 2018a), cities (Pulselli et al., 2008; Sevegnani et al., 2017), watershed (Agostinho et al., 2010; Pulselli et al., 2011), high tech equipment (Di Salvo et al., 2017) and countries (Giannetti et al., 2013b).

Some research works focusing on milk production, which is the subject of this work, can be quoted: (i) Studying milk production farms in Chiapas, México, Alfaro-Arguello et al. (2010) stated that local knowledge and the understanding of how the surround natural environment works can improve the emergy performance of milk production towards holistic ranches; (ii) Teixeira (2011) provided a comparison between a conventional milk production system with a more holistic system named *"silvopastoril"* in Brazil, in which the latter obtained better emergy performance than the former; (iii),assessing an integrated milk farm in Argentina based on rotation of cash crops and pasture, Rótolo et al. (2012) emphasize this production system as being able to appropriate largely of local renewable resources and possessing low load on the natural environment; (iv) considering four different production system as case study located in France-colonized territory in Africa, Vigne et al. (2013) highlights the importance of correctly choosing the scale of analysis in emergy synthesis, by ranging the system boundaries; (v) evaluating nine dairy farms in Slovenia by using emergy synthesis and economic indicators, Jaklic et al. (2014) points out the discrepancy between economic and emergy findings, as while the former supports large scale and traditional milk production, the latter supports small scale and organic based production; (vi) incorporating biophysical criteria into a standard socio-economic optimization model to assess the sustainability of Slovenian dairy sector, Kocjancic et al. (2018) have found that further expansion of small conventional farms is not justified and that organic production plays a substantial role to achieve higher degrees of sustainability. Although focusing on milk production, the results of these studies are site specific, or different approaches were considered to assess sustainability, which makes it difficult and, sometimes, impossible to generalize their results for the Brazilian case. Additionally, regional analysis assessing alternatives for development are seldom found in literature, which implies some barriers for decisions on a regional strategic planning towards regional sustainable milk production.

This work aims (i) to assess the environmental performance of different milk production systems located at southern region of Minas Gerais state, Brazil, and (ii) explore alternatives to achieve a regional sustainable milk production.

2. Methods

2.1. Systems description and primary data gathering

According to the Brazilian Institute of Geography and Statistics (IBGE, 2013), Minas Gerais state is the largest milk producer in Brazil, achieving 27% of the overall Brazilian production. With 1.2 million hectares of land occupied with pasture grazing, the southern region (118 cities, amounting to 3.7 million hectares; Fig. 1) is recognized as the most important region, as far as milk production is concerned. Raw data were obtained through fieldwork by applying surveys to 92 local milk producers, totaling 49 randomly distributed cities. It is important to emphasize that the boundaries of the evaluated systems are restricted to milk production, including pasture land, milk house, equipment, as well as the production (when any) of corn, soybean and/or other biomass to produce cattle feed; natural vegetation areas and others not directly related to milk production are disregarded. This is important as it allows for a comparison among the milk production systems,

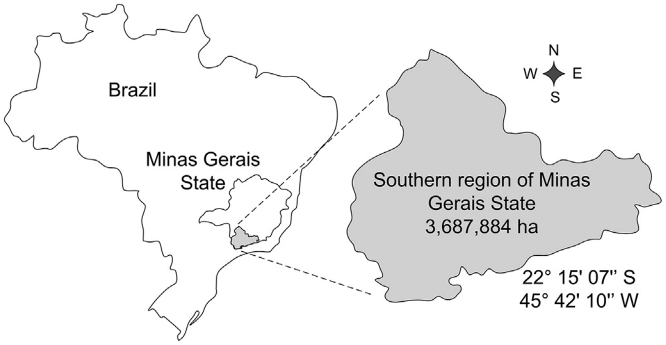

Fig. 1. Geographic location of the southern region of Minas Gerais state, Brazil.

exclusively, preventing from the influence of different scales of analysis, as identified by Vigne et al. (2013).

Different types of milk production system co-exist in the region, each one featuring different productivity indices, handling methods, intensity of labor, and use of energy and external materials. Based upon animal productivity and the level of technology available, the most important agricultural research center in Brazil (Assis et al., 2005) classifies milk production systems into four main types: (i) extensive system: per animal productivity below 1200 L/yr with animals raised exclusively by grazing; (ii) semi-intensive system: per animal productivity between 1200 e 2000 L/yr, graze-raised with supplementary volume during dry pasture periods; (iii) pasture intensive system: 2000–4500 L/yr productivity, graze-raised with high nutritional quality forage and supplementary volume throughout the year, or part of it; (iv) confinement intensive system: per animal productivity above 4500 L/yr, trough-fed and full confinement.

As detailed as such classification can be, during the fieldwork period for collection of primary data in the 92 rural properties, an operational difficulty was faced in clearly framing the production units into the four types previously defined (extensive, semi-intensive, pasture intensive, and confinement intensive). Thus, the call for a cluster analysis was identified. For that purpose, the 92 studied production systems were reclassified into three types: (i) extensive system: cattle raised in pasture, with supplementary forage in times of dry pastures; (ii) semi-intensive system: cattle raised in pasture with supplementary volume and forage throughout the year; (iii) intensive system: total confinement, feeding based on ration and forage throughout the year. This new classification was validated in common agreement with the technical staffs of "Instituto Mineiro de Agropecuária" (IMA), "Empresa de Assistência Técnica e Extensão Rural do Estado de Minas Gerais" (EMATER), and some regional dairy industries. After reclassification, the following indicators were established in common agreement (personal interviews and/or participative meetings) with experts of IMA and EMATER and considered for the Cluster analysis: (i) L_{milk}/ha/yr; (ii) L_{milk}/labor-hours/day; (iii) L_{milk}/cow/day; (iv) livestock/$ha_{pasture}$; (v) kWh/L_{milk}/yr; (vi) kg_{feed}/L_{milk}/yr; (vii) cattle breed. The add-in "Action 2.5" (www.portalaction.com.br) for Microsoft Excel® is used for the clustering analysis considering the hierarchical method, Euclidean distance and median approach as parameters. This approach allows for the inclusion of each one of the 92 studied rural properties into groups with similar characteristics expressed by the indicators considered within cluster analysis.

After clustering, rather than calculating average values for each obtained clustering group, one single representative milk production property is chosen as a reference by considering the L_{milk}/cow.day indicator as a criterion. To achieve this, the property featuring the productivity level closest to the average productivity level is selected as the referential one for the cluster group. Such approach was assumed in order to avoid establishing a "hypothetical" system.

2.2. Environmental accounting based on emergy

H.T Odum (1996) developed the emergy accounting based on the energy analysis of biological systems, systems general theory, and system ecology to account for all energy from natural environment embodied in the development of processes and services. Emergy is defined as "the available energy of one kind previously used up directly and indirectly to make a service or product". All energy and materials flows that cross the boundaries of system under study, whether originating from natural environment or even from the larger economic system, are converted into the same kind of energy unit, named solar emjoule (sej); for such a transformation, the unit emergy values (UEVs) are used. Considering the work done by nature to generate and make all resources used by the human-made systems available, emergy provides a donor-side perspective in measuring the "quality" of energy under a larger scale perspective, suggesting a hierarchical chain of energy in space and time. The quality of energy in emergy accounting is expressed quantitatively by the UEV, a ratio between all emergy used up by a system (input flows) and its output flows (Fig. 2).

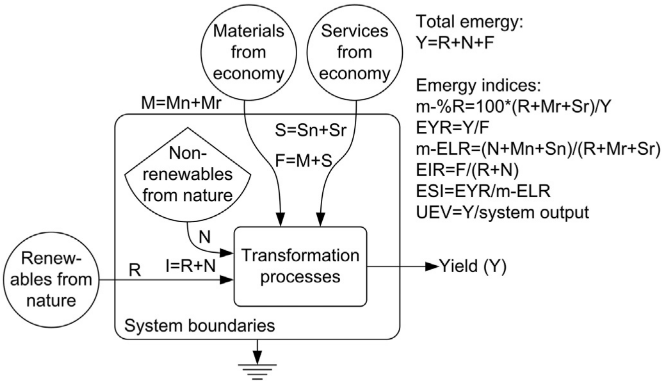

Fig. 2. Generic energy diagram containing symbols, nomenclature, and indices usually considered in emergy synthesis. Uppercase and lowercase letters "r", "R", "n" and "N" stand for renewable and non-renewable respectively, while "m" means modified from original. M = materials; S = services; F = feedback from economy; I = indigenous natural resources; Y = total emergy driving a process or system. The meanings of emergy indices are explained in the main text.

Emergy synthesis starts with the identification and representation of the system under study on an energy diagram, in which all input and output flows crossing system boundaries are identified. Symbols proposed by Odum (1996) are used (Fig. 2) for this task. The second step includes the elaboration of an emergy accounting table that quantifies all previous system input flows, preferentially in units of energy or mass; the total input of each flow will be multiplied by its respective unit emergy value (UEV), or more specifically, the transformity (sej/J), emergy per money ratio (sej/$) or specific emergy (sej/g). The third and final step is to calculate the emergy indices (Fig. 2) to support discussions on the system emergy performance. For details on emergy accounting definitions and procedures, please refer to Odum (1996). A brief definition of emergy indices used in this work is presented below:

(a) Renewability, %R = (R + Mr. + Sr) / Y, is the ratio of renewable emergy to total emergy use. It ranges from 0 to 100%, where higher values mean better rating. In the long periods, only processes with high renewability can be sustained (Brown and Ulgiati, 2004).
(b) The Emergy Yield Ratio, EYR = Y/F, is the ratio of the total emergy driving a process to the imported emergy. It is a measure of the system's ability to exploit the local natural resources by means of an external resource investment from the outside economic system, and reflects the potential contribution of the process to the main economy (Brown and Ulgiati, 2004).
(c) The Environmental Loading Ratio, ELR = (Mn + Sn + N/ (R + Mr. + Sr), is the ratio of non-renewable and imported emergy use to renewable emergy use. It indicates the pressure produced by the system on the environment and can be considered as a measure of ecosystem stress (i.e., distance from a system state supported by renewable sources only). According to Brown and Ulgiati (2004), ELR values lower than 2 indicate low pressure on local environment; values between 2 and 10 mean moderate load; values higher than 10 mean high pressure and impact.
(d) Emergy Investment Ratio, EIR = F/(R + N), indicates the effectiveness of an investment to drive a local development process. Depending on the process that is implemented, the same resource invested may make it possible to exploit different amounts of resources. According to Brown and Ulgiati (2004), the EIR indicates if a process makes good use of the emergy invested, in comparison with alternatives.
(e) The Emergy Sustainability Index, ESI = EYR/ELR, is an aggregated

indicator which links the characteristics of EYR to those of the ELR. It responds to the goal of relying on the largest possible amount of local resources in a process at the lowest possible environmental loading rate (Brown and Ulgiati, 2004). Although an important index, Bastianoni et al. (2007) emphasizes that, being a ratio of ratios, the ESI hides a large amount of information, and therefore it must be handled carefully.

(f) Unit Emergy Value (UEV) is the general label for all emergy intensities, i.e. it is defined as the solar emergy required to make one unit of a system's product output (regardless of the output measure unit: energy, mass, as well as any other kind of unit). It is calculated by the ratio of total emergy (Y) that driving a process to the product amount (UEV = Y/system output). UEV is an expression of the supply-side quality of the output itself, for the higher the UEV, the more emergy required to make the product flow.

In this work, the %R and ELR indices are calculated by considering the partial renewability of inputs according to the proposition of Tiezzi and Marchettini (1999), further assessed by Ortega et al. (2002), used by Agostinho and Ortega (2012, 2013) and Agostinho et al. (2008), and recognized by Ulgiati and Brown (2014). The inclusion of partial renewabilities is an attempt to include the renewability of each system input by expanding the boundary of their generation and supply process. This approach is particularly appropriate when the system uses materials and labor from local or regional economy, which could be renewable or, at least, partially renewable. The assumed partial renewability values for some inputs as done in this work were based on authors' experience and from published scientific works; calculation details are presented on Appendix A.

Emergy accounting is applied in this work to assess each identified milk production group individually, but also in supplying information to understand the functioning and improvement potentials for milk production on a regional scale. Thus, the methodological approach can be divided into two main steps: (i) diagnosis, in which emergy accounting is applied to calculate the emergy indices and allows comparisons among the different identified milk producer groups; (ii) management, in which the potential to improve the overall regional emergy performance is explored. Both approaches are presented separately, in the following sections.

2.2.1. Diagnosis step: emergy accounting

2.2.1.1. Emergy accounting and Monte Carlo simulation. After establishing the milk production systems under cluster analysis, emergy synthesis is applied to assess all identified milk production groups. Recognizing the importance of assessing uncertainties in emergy evaluations, a Monte Carlo simulation is performed (Fig. 3) by randomly varying the unit emergy values (UEVs) range borrowed from emergy literature (Appendix B), as well as the partial renewability of underground water, electricity, emergy per money ratio of Brazil, and labor inputs (Appendix A). The Monte Carlo simulation is performed by means of an Excel® add-in (Barreto and Howland, 2006) and assuming a triangular probabilistic distribution function under 10,000 interactions; a similar procedure was previously used by Agostinho et al. (2015). The results of this simulation are the average of emergy flows for each milk production system group previously identified through the clustering analysis, which allows for the calculation of emergy indices for each group.

2.2.1.2. Ternary diagram. The emergy ternary diagram proposed by Giannetti et al. (2006) is used to graphically represent the emergy results of this study. Ternary diagrams have been used to support and summarize emergy assessments under an easy interpretation, as well as allowing for different viewpoints regarding patterns and tendencies. Different studies have used the ternary diagram, such as the ones on large watersheds (Agostinho et al., 2010), industrial and agricultural production systems (Almeida et al., 2007; Agostinho et al., 2008; Cai et al., 2008), urban solid waste management (Agostinho et al., 2013), biodiesel alternatives (Ren et al., 2013), and interactions of human-dominated systems with the natural environment (Giannetti et al., 2011). The emergy ternary diagram comprises three components: renewable (R), non-renewable (N), and imported from the largest economy (F), represented over an equilateral triangle. Each corner refers to a component, and each side to a binary system. Ternary combinations are identified by points within the triangle, in which the relative proportions of the three components are indicated by their geometric projections onto one of the sides. For detailed information and examples of use, please refer to Giannetti et al. (2006) and Almeida et al. (2007).

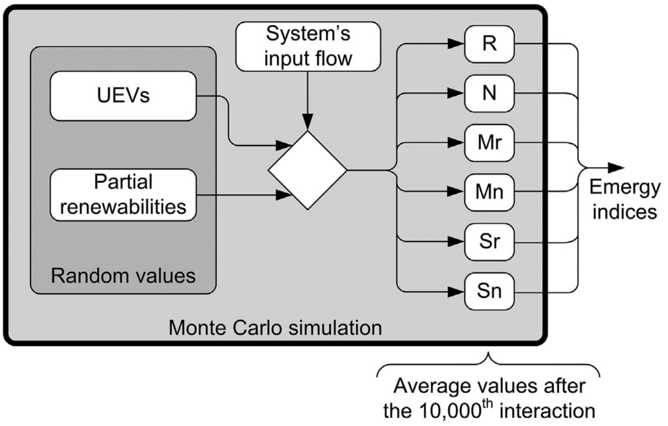

Fig. 3. Scheme of emergy indices calculation procedure.

2.2.2. Management step: exploring alternatives for development

According to Odum (1996), “since economic development is apparently empower[1]-dependent, emergy accounting can be used to choose development plans that can be sustained”. Considering the temporal and spatial scales of a regional economic development, productivity depends on the interaction between natural resources (“I”, with low unit emergy value) with purchased resources (“F”, with higher unit emergy value) in a matching process. In this sense, the emergy investment ratio index (EIR = F/I) could be used to assess whether this match contributes most to the system productivity, and for this purpose Odum (1996) proposes three main approaches as followed described.

Under the limiting factors concept, any input to a system can become a limiting one when the other factor or factors are available in excess. This statement supports that the best use of emergy flow for maximizing production comes when the purchased emergy (F) matches with the emergy from natural sources (I). Matching emergy inflows means balancing potential limiting factors to production, and in this case, “emergy is efficiently used when applied equally to both inputs” (Odum, 1996). This first approach to assess alternatives for development suggests an EIR equal to 1.

Additionally to the limiting factor, the second approach assumes that curve of diminishing returns concept can also be considered to support the premise of using EIR index to assess alternatives for regional development. Under the diminishing return concept, the larger emergy of an input (usually F) in relation to other (I in this case) results in an increase of production, but at a lower rate; this is recognized as business-as-usual. High production under lower rates increase the EIR index, and again, “emergy is less efficiently used” (Odum, 1996).

Assuming that the systems that prevail are those that make more emergy available and utilize it more efficiently, then systems with greater empower are more likely to continue. The EIR that represents

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[1] Empower is defined as emergy flow per unit time (units: emjoules per unit time; Odum, 1996).

an efficient use of emergy would be that equal to 1. However, a region containing production systems characterized by a low EIR – and an EIR of 1 is considered low – may be unable to maintain this developing pattern due to a large potential for regional economic growth. This means that more intensive production systems (i.e., EIRs higher than 1) can displace the less intensive ones. Thus, according to Odum (1996), the production system's EIR considered as "sustainable tends to be that of the region", and this is the third approach in assessing alternatives for development. The regional EIR can be used to estimate the potential for development of a production system by multiplying the demanded system's natural resources (I) by the regional EIR, which results in the so-called area's emergy attraction value.

Among the three previous presented approaches as suggested in Odum's (1996) book to assess alternatives for development by balancing the system's EIR with the regional's EIR, the emergy of potential matching is the one considered in this work. It was chosen due to the inherent difficulty in managing the natural renewable resources represented by the "I" input – e.g. increasing the amount of rainfall going into the system. The goal is to reach the economic matching that could result if the system's original emergy flow from natural sources ("I") were retained and matched with the purchased resources ("F"), according to the regional EIR. This is performed in two steps: (#1) assessing the potential match alternatives under a macroscopic view, or focusing exclusively on upstream impacts; (#2) assessing the combination of milk production systems aiming to reach the previously chosen best alternative.

- Step #1: The regional EIR index is initially estimated; "R" resources are estimated by considering the regional natural resources such as solar radiation, rainfall, and wind; an average "N" is estimated as soil loss according to the regional land use; "F" is estimated by considering the monogram published in Odum (Odum, 1996, Fig. 5.2. pg. 76). Estimating the regional demand for "R" and "N" resources is usually an easier task than estimating "F" resources, because the latter depends on a large number of data regarding importation, which is rarely found in statistics dataset for regional boundaries in Brazil. After estimating the regional EIR, four main approaches are considered to evaluate potential alternative developments: (a) considering the currently existing milk production systems in the region and their demand for "R", "N", and "F" resources, herein named "original" approach; (b) the replacement of low productivity family-managed properties by others with higher productivity as envisioned by the Brazilian government through the "Minas Leite" program; (c) regional matching by maintaining the current dependence of "R" and "N" resources for milk production and estimating the optimal "F" dependence to reach the same EIR of the region; (d) emergy matching by maintaining the current dependence of "R" and "N" resources and adopting the same amount for purchased emergy ("F"), resulting in an EIR of 1, which represents the absence of a non-limiting input factor.
- Step #2: After choosing the most appropriate of the four assessed alternatives for development of milk production (i.e. original, "minas leite" scenario, regional matching, or emergy matching), this following step consists of randomly combining milk production areas occupied with the different production systems as identified through cluster analysis, in an attempt to reach the previously established regional EIR. For this purpose, a mathematical combinatorial optimization approach is used (only integer numbers are considered). A database (MySQL) containing all possible combinations is used for combinatorial analysis.

3. Results and discussions

3.1. Establishing the representative milk production systems

Table 1 shows the milk production systems defined – or groups as

Table 1
Clustering approach result[a]. Groups and their milk production systems, average for group milk productivity, and the milk production system representative for the entire group.

Group	Classification	Milk production systems	Average for L_{milk}/cow per day	System chosen as representative for the group[b]
G1	Semi-intensive	77	21	77
G2	Semi-intensive	47, 48, 49, 52, 53, 54, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87	12	60
G3	Extensive	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 50, 51, 55	55	46
G4	Intensive	88, 89, 90	20	88
G5	Intensive	91, 92	32	91

[a] Cluster dendrogram is presented at Supplementary Material SM-A.

[b] G1, system 77: 290 ha, 4400 L_{milk}/day, 21 L_{milk}/cow/day; G2, system 60: 26 ha, 360 L_{milk}/day, 12 L_{milk}/cow/day; G3, system 46: 19 ha, 33 L_{milk}/day, 5.5 L_{milk}/cow/day; G4, system 88: 23 ha, 1060 L_{milk}/day, 20 L_{milk}/cow/day; G5, system 91 (property 91 was chosen because it is more representative than 92): 130 ha, 3500 L_{milk}/day, 32 L_{milk}/cow/day.

labeled herein – resulting from the clustering approach. Please refer to Supplementary Material SM-A for details on cluster analysis results The maximum number of groups that clearly represent the different milk production systems as a result of cluster analysis was established by the authors with support from specialists of cattle management for milk production of "Instituto Mineiro de Agropecuária" (IMA) and "Empresa de Assistência Técnica e Extensão Rural do Estado de Minas Gerais" (EMATER). Groups G1 and G2 represent semi-intensive systems. Group G1 is characterized by high use of inputs such as feed, "Dutch" breed cattle, picket line-grazing, several employees with different education levels, yielding 4400 L_{milk}/day, with a 21 L_{milk}/cow day average; a G1 group is rarely found in Brazil, as it demands the highest specialized knowledge on milk production. Group G2 represents a small semi-intensive system, producing 360 L_{milk}/day, featuring treated pasture, complementing the half-breed cattle feeding with ration and reaching a productivity of 12 L_{milk}/cow/day. Group G3 is an extensive system that comprises 48 properties from the 92 total and represents the lowest intensity milk production in the region. G3 is characterized by degraded-pasture feed complemented with forages during the winter, low-educated family labor, half-breed cattle, its yield is 33 L_{milk}/day and productivity is 5.5 L_{milk}/cow/day. The remaining Groups G4 and G5 are classified as the intensive ones, which both use the "free-stall" model for Dutch cattle confinement, feeding based on ration and forages throughout the year. The difference between G4 and G5 is in the quantity of inputs and in the technology used. The higher technified G5 uses more labor and land for milk production, yielding 3500 L_{milk}/day, averaging 32 L_{milk}/cow/day. The G4, featuring less use of technology and labor, yields 1060 L_{milk}/day, and has lower productivity, at 20 L_{milk}/cow/day, comparable with other intensive systems in the region.

After clustering, rather than establishing an average value to define a hypothetical representative system of each group, the productivity in L_{milk}/cow/day was the criterion used for selecting the actual representative system. In short, Table 1 shows that properties 77, 60, 46, 88 and 91 were selected as representatives for G1, G2, G3, G4 and G5 groups respectively.

3.2. Emergy synthesis for the five identified milk production groups

Fig. 4 represents the energy diagram for all five milk production groups assessed in this work. A single diagram is considered to represent all groups, since all have similar characteristics as for energy and material inputs and outputs, differing basically on the amount of resources inflowing to the system. The most evident differences among the intensive system (G3) and the semi-intensive ones (G1 and G2) are in bold type in the diagram, e.g., the use of pickets (for rotational grazing) in the pasture lands, the demand for high genetic potential semen, the use of ration as feed supplement, automatized milking, and improvements in accounting-managerial questions; all such features are present in the semi-intensive systems, which results in productivity increase, as compared to the extensive system. The intensive systems feature the same characteristics mentioned above, except that the animals are totally confined, therefore the pasture - colored gray in the diagram - is not assigned to groups G4 and G5, as the animals in these are exclusively ration-fed.

Table 2 presents the emergy indexes for the five milk production groups under study herein. Since the Monte Carlo approach was applied due to uncertainties on partial renewabilities and UEVs used in the emergy synthesis, the emergy tables are not featured in the main text of this work, however, they are provided as electronic sheets in the Supplementary Material SM-H. Ten thousand repetitions were assumed when running the Monte Carlo simulation, which implies the same amount of emergy tables and justifies their being available as electronic files. Some characteristics of all other milk production systems presented in Table 2 as for comparison are described as follows: (i) SF is a farm located in Santa Fé, an important dairy producing center in Argentina, featuring good intensification level, studied by Rótolo et al. (2012); (ii) Teixeira (2011) assessed the Santa Edwiges (SE) farm, with semi-intensive management, and the Boa Vista (BV) farm, with semi-intensive management including forestry in the pasture areas, both located in Lavras, Minas Gerais, Brazil; (iii) South of Mali (SM), a system similar to the extensive G3 of Brazil, Reunion Island (RI), with high energy consumption, and Poitou-Charentes (PC), featuring intermediate energy consumption level were all studied by Vigne et al. (2013); (iv) the farm in Alto do Araúma, in the state of São Paulo, Brazil, assessed by Mendes et al. (2012); (v) farm under conventional (CS) and organic (OS) milk production management, both in Sweden, and studied by Brandt-Williams and Fogelberg (2004).

The G3 group, representative of the extensive milk-production systems, had the best performance regarding %R, by reaching 29%; this value is from 1.6 to 2.5 times higher than the other assessed Brazilian systems. In comparison with values found in literature, the %R for G3 is close to those for the SF and SE systems. It is noteworthy that the SF is higher in intensification, comparable to the Brazilian G1, however, the %R of the latter is 14%. With 44%, SM shows high use of renewable resources, which also occurs with BV (40%). The %R of 21, 21, and 24%, respectively, for RI, PC and BR systems evidence better performances than those from the intensive and semi-intensive Brazilian systems; this indicates potential improvements for G1, G2, G4 and G5. It is also interesting to note that milk labeled as "organic" has been achieving larger market acceptance worldwide, despite having one of the lowest %R, which indicates that, a priori, organic milk is not synonymous of renewable, nor of sustainable product, since its emergy sustainability index (ESI) achieved a low score of 0.14. Although organic milk is defined as non-dependent on industrial fertilizers, ration and medicines, this production systems is still highly dependent on resources from the larger economy (proportion of 7:1 of purchased resources by the local resources as disclosed by Brandt-Williams and Fogelberg, 2004) that are mostly based on fossil energy, which results in low sustainability according to emergy accounting principles.

As for the emergy yield ratio (EYR), the best performance was achieved by the G3, at 1.72, whereas the worst performances were obtained by G4 and G5, at 1.06 and 1.08, respectively. A pure conversion process gives EYR = 1, while higher EYR values mean that each unit of investment from outside is amplified and then returns higher amounts of emergy to the larger economic system. Results from Table 2 indicate SM, G3 and SF (1.89, 1.72 and 1.58) as the ones capable of providing higher amounts of emergy to society than all other compared milk production systems that have values closer to 1. This tendency indicates that milk production systems, at least for those presented in Table 2, have low efficiency at making natural resources available to society.

For the Brazilian milk systems, the obtained emergy to environmental loading ratio (ELR) indicates that G1, G2, G4 and G5 have been causing a moderate load on the natural environment ($3 < ELR < 10$) by pushing the natural capital into providing with non-renewable resources; G3 shows low load with $ELR < 3$, precisely 2.46. Table 2 shows a high range (from 1.5 to 46) for ELR performance of milk production, with special attention to the CS and OS Swedish systems scoring 46 and 8, respectively, because these are the highest values in the set of farms.

Odum (1996) argues that low values for emergy investment ratio (EIR) can be considered positive, under an economical competition, since low EIR indicates production systems able to demand more emergy from the natural environment (considered free-of-charge) and reducing the demand for emergy from the larger economic system. In this sense, while G3 shows the best performance as for EIR (1.39), the G4 yields the worst performance (16.6). The highest dependence on resources from economy makes G4 less resilient to external disturbance on market, therefore it must always be on alert about the availability of its input resources, as well as its outputs (milk), seeking balance between both, in order to avoid high disturbances. Table 2 shows G3, SF and SM as the best overall performers, whereas all other systems have

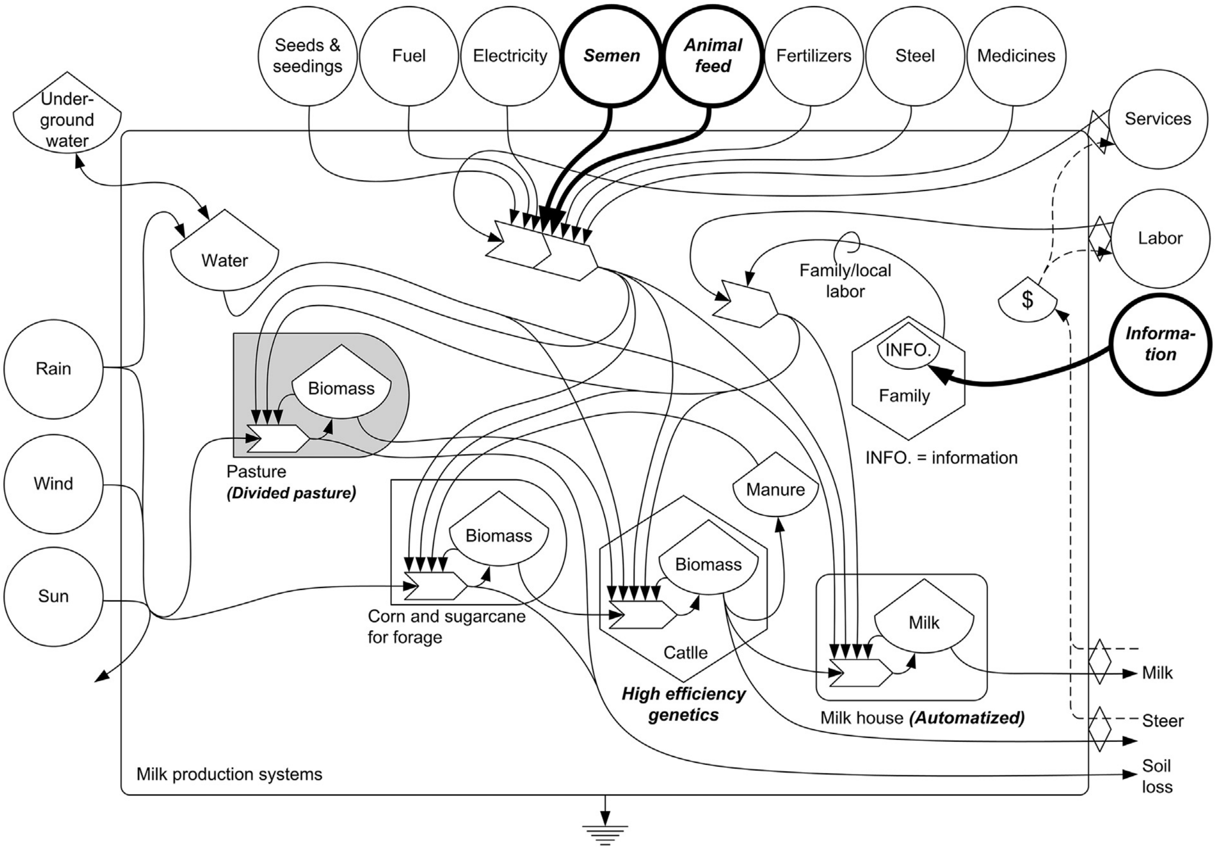

Fig. 4. Energy diagram representing the five evaluated milk production systems. The external circle symbols in bold with texts in italics (representing semen, animal feed and information) are absent for G3 system. The internal symbol in gray representing pasture areas exist exclusively for G1–G2 and G3 systems; G3 has an open pasture while G1–G2 have divided pasture. G1–G2 and G4–G5 have high efficiency genetics and an automatized milk house.

EIR > 3, indicating their dependence on about three times more resources from the economy than from the natural environment. The value of 37.4 obtained by Sweden's CS system draws attention, since its EIR is two times as high as those for the highly intensive milk producers in Brazil (G4 and G5).

To synthesize, the G3 system obtained the best performance among all in terms of ESI by achieving 0.70, which can be visualized on Fig. 5. By comparing all other milk production systems, Table 2 shows that SM was the only one able to achieve an ESI value (1.51) considered as sustainable in the medium term. The low performance obtained for ESI indicates that the milk production systems on Table 2 provide low emergy to society by causing high load on the natural environment. Interesting to note, on Fig. 5, the presence of a sensitivity line, indicating that the semi-intensive and intensive milk production systems (G1, G2, G4 and G5) share the peculiarity of maintaining the proportions of "R" and "N" emergy demand by changing their dependence on "F" resources.

In general, considering the above-presented five emergy indicators focused in the upstream impacts on the natural environment, it seems clear that G3 system should be promoted, since it achieved the best performance for all indicators, among the milk production groups evaluated. This result was expected, since G3 is a family-managed small-property that demands low amounts of external resources to produce milk. On the other hand, decisions should also consider the

Table 2
Emergy indices for milk production systems.

Emergy indices[a]	Milk production systems[b]													
	G1	G2	G3	G4	G5	SF	SE	BV	SM	RI	PC	AA	CS	OS
%R, in %	14.8	17.8	28.9	11.3	11.7	29.55	33.54	40.03	44.0	21.0	21.1	14.83	2.12	11.0
EYR	1.15	1.17	1.72	1.06	1.08	1.58	1.18	1.10	1.89	1.34	1.13	1.18	1.03	1.14
ELR	5.73	4.62	2.46	7.88	7.52	2.37	1.98	1.5	1.25	3.86	4.39	5.90	46.08	8.01
EIR	6.73	5.79	1.39	16.60	12.22	1.72	5.5	9.18	1.12	2.95	3.95	5.73	37.4	7.19
ESI	0.20	0.25	0.70	0.13	0.14	0.67	0.59	0.73	1.51	0.35	0.26	0.20	0.02	0.14
Y, in E15 sej/ha yr	28.69	25.05	10.88	111.92	64.62	–	–	–	–	–	–	–	–	–
UEV, in E12 sej/L_{milk}	3.25	3.62	15.67	6.39	5.01	–	0.02	0.07	1.51	4.06	0.62	2.35	–	–
UEV, in E6 sej/J_{milk}	1.29	1.45	6.01	2.40	1.93	–	–	–	–	–	–	–	–	–

[a] Calculation details at Appendix D.

[b] G1, G2, G3, G4, G5 = milk production systems evaluated in this work; SF = Santa Fé, Argentina (Rótolo et al., 2012); SE = Santa Edwiges, Brazil (Teixeira, 2011); BV = Boa Vista, Brazil (Teixeira, 2011); SM = South Mali, Africa (Vigne et al., 2013); RI = Reunion Island, Africa (Vigne et al., 2013); PC = Poitou-Charentes, France (Vigne et al., 2013); AA = Alto do Araúma, Brazil (Mendes et al., 2012); CS = Conventional management, Sweden (Brandt-Williams and Fogelberg, 2004); OS = organic management, Sweden (Brandt-Williams and Fogelberg, 2004). Further details about each system presented in the main text.

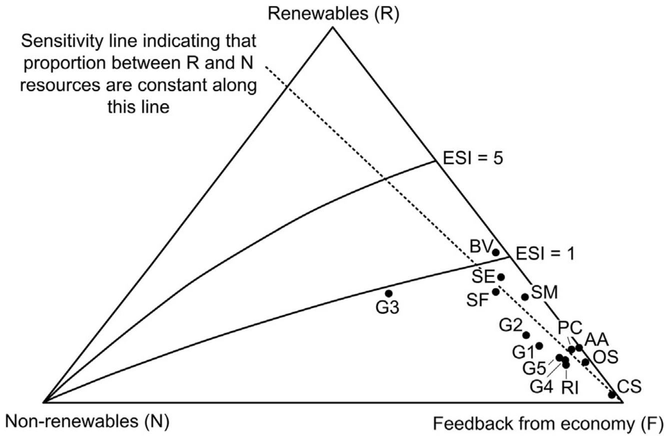

Fig. 5. Ternary diagram showing the emergy performance for the five milk production systems evaluated in this work. Legend: ESI = emergy sustainability index; G1, G2, G3, G4, G5 = milk production systems evaluated in this work; SF = Santa Fé, Argentina (Rótolo et al., 2012); SE = Santa Edwiges, Brazil (Teixeira, 2011); BV = Boa Vista, Brazil (Teixeira, 2011); SM = South Mali, Africa (Vigne et al., 2013); RI = Reunion Island, Africa (Vigne et al., 2013); PC = Poitou-Charentes, France (Vigne et al., 2013); AA = Alto do Araúma, Brazil (Mendes et al., 2012); CS = Conventional management, Sweden (Brandt-Williams and Fogelberg, 2004); OS = organic management, Sweden (Brandt-Williams and Fogelberg, 2004).

system outputs, since they are, by definition, production systems. Considering the efficiency indicator expressed by the UEVs on Table 2 (it is, in fact, the inverse of UEV, as we are dealing with output/input ratio), the performance of G3 is now the worst, followed by G4-G5 and G1-G2 in the main positions. While G1 demands 3.25 E12 sej to produce 1 L of milk, G3 demands 4.8 times more emergy (15.67 E12 sej); in other words, G3 demands more global resources to produce 1 L of milk than all other evaluated groups, thus indicating the lowest efficiency.

The existing trade-off between the most sustainable production systems under upstream impact assessment with the importance of products (i.e. outputs) to supply the society needs was also identified and discussed by other authors, for instance, in the work of Agostinho and Ortega (2012) and Kocjancic et al. (2018). A win-win production system with high sustainability and efficiency will hardly ever be found, which claims for a different approach for diagnosis when making decisions towards sustainability. In this sense, Bonilla et al. (2010) proposed the use of a graph relating the emergy index ESI with what the authors called "global efficiency" (the inverse of UEV). The proposition is that highest area means higher overall performance by combining both fundamental indicators supporting decisions on sustainability. Fig. 6 proposes a hierarchy, starting from the most sustainable milk production system assessed: G2, G1, G3, G5 and G4. Thus, assuming the premise that sustainability must account for the upstream impacts (measured by emergy accounting) as well the system outputs, then the G2 system should be promoted under political and economic incentives.

3.3. Alternatives for development

After completing the diagnosis step, in which the representative milk production systems found in southern Minas Gerais are quantified to identify differences and potential for improvements, the obtained values can now be considered to support a discussion on alternatives for development under a large-scale perspective. This approach is mainly important to support decisions towards a regional planning for sustainable milk production. For this propose, two different approaches are separately presented: (i) focusing on the upstream impacts under the emergy accounting view, and (ii) focusing on the upstream impacts and the amount of milk produced.

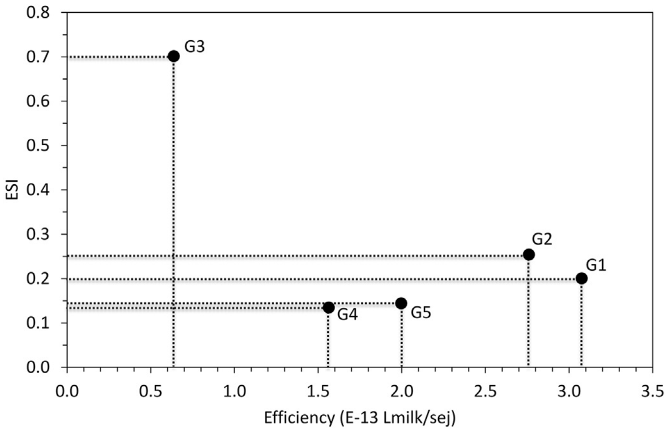

Fig. 6. Relationship between global efficiency and the emergy sustainability index (ESI). Area within lines, from best to worst performance: G2 = 0.70; G1 = 0.62; G3 = 0.45; G5 = 0.29; G4 = 0.21.

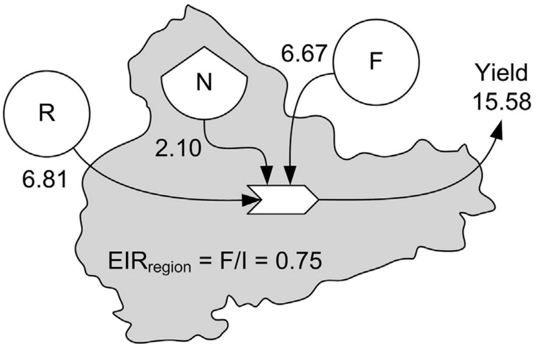

Fig. 7. Three arm diagram for the southern region of Minas Gerais State. Values in E21 sej/yr. Calculation details in Appendix E.

3.3.1. Focusing exclusively on upstream impacts

Fig. 7 represents the three-arm diagram of southern Minas Gerais. Values are estimated under a top-down approach, considering the system as a whole; calculation details are presented in Appendix E. Values show a dependence on "R" resources of 6.81 E21 sej/yr, a value 3.2 times higher than "N", but similar to "F" resources. These numbers result in a regional EIR of 0.75, whereas the Brazilian EIR is 0.36 (Sweeney et al., 2007) and the value for Minas Gerais State is 0.08 (Demétrio, 2012). This EIR performance indicates that about 0.75 solar emjoule from "F" is necessary for each solar emjoule from the "I" source used by the region.

The Brazilian government's intention of replacing primitive milk production systems (G3) with the more economic ones (G2) – namely, the "Minas Leite program" – can be seen as an alternative policies for growth while there are sources of cheap emergy available to purchase from, basically fossil emergy. On the other hand, when exploring alternatives for development, considering not the empower exclusively, but also the efficiency in emergy use under a regional perspective, the figures do change somewhat. Fig. 8 shows four different alternatives for milk production development by considering these aspects, and the interpretation is as follows:

(a) Original alternative: The current milk production in the region is based on unsustainable management, as it depends on higher amounts of "F" than "I" resources, resulting in an EIR of 2.39. This uneven emergy inflow results in an EIR ratio higher than the regional average of 0.75, as shown in Fig. 7. Within short term, this development pattern for milk production can prevail when compared to the primitive systems (e.i., the more ecological ones with lower dependence on "F"), however, when the "F" resources

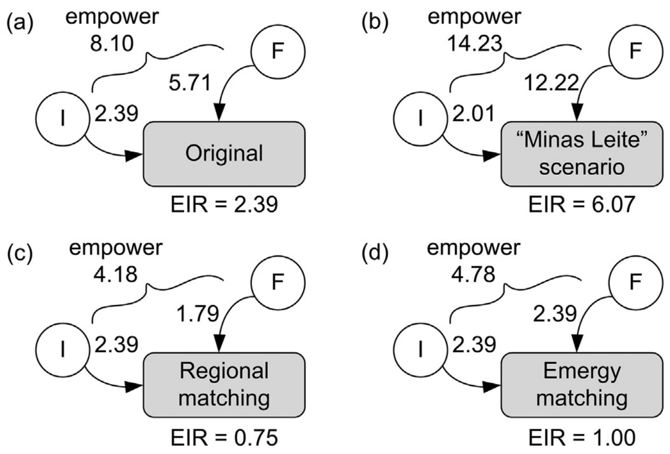

Fig. 8. Exploring alternatives for milk production development in the southern region of Minas Gerais state under the emergy investment ration (EIR) bases. Emergy flows in E21 sej/yr; Feedback from the larger economy (F); Indigenous resources (I); Calculation details in Appendix D.

become expensive and/or unavailable due to fossil fuels shortage, such scenario could break down and reduce its intensity.

(b) The "Minas Leite" alternative: The government's intention to intensify milk production is represented in this scenario, by replacing all the G3 systems with the G2 systems. This scenario can be considered as a worse alternative than the original one. The "Minas Leite" alternative is unsustainable due to the increase in "F" dependence, when compared to the original alternative, resulting in an EIR of 6.07; this ratio is nearly two times higher than the original alternative. The uneven emergy matching increases empower from 8.10 to 14.23 E21 seJ/yr, but emergy is less efficiently used. Within a short term, this alternative can prevail over all the other ones assessed here due to its economic power. However, in a scenario with lower oil availability, it could break down and cause higher damages (economic and social), when compared to the original alternative.

(c) Regional matching alternative: Differently from highly developed regions (i.e., regions with high "F" dependence), the southern region of Minas Gerais state, as studied herein, demands larger amounts of "I" than "F" resources; such characteristic results in a regional EIR of 0.75. When using this regional EIR as a parameter to match the milk production EIR, the resulting "F" inflow (1.79 E21 sej/yr) becomes lower than the "I" inflow (2.39 E21 sej/yr) and creates a scenario containing a limiting factor, in which "I" resources inflows are limited by "F". This alternative is considered as unbalanced, resulting in an inefficient use of emergy. Its sustainability can be considered as higher than those of the two previous alternatives due to its lower "F" dependence, as compared to "I", however, its empower is lower as well and cannot compete with alternative systems in the short term.

(d) Emergy matching alternative: as far as the efficient use of emergy and sustainability are concerned, this scenario could be considered as the best alternative among all. The balance between "F" and "I" inflows results in no limiting factors in the milk production sector, thus emergy is used efficiently to maximize production. Additionally, this alternative demands a reduced amount of "F" resources, in comparison with the Regional Matching alternative, which guarantees higher power in the market competition at a higher sustainability degree.

Focusing on the upstream impacts, as evaluated through emergy accounting, the alternative that matches emergy use (alternative "d") achieves the best performance of all, therefore, it should be used to support policies regarding a more sustainable milk production in the assessed region. This would require a reduction of about 2.4 times the current dependence on "F" resources (from 5.71 to 2.39); in case the "Minas Leite" scenario gets implemented, the demand of "F" resources will be reduced in about 5.1 times (from 12.22 to 2.39). Is this achievable? How to provide technical alternatives and economical incentives for producers aiming for a sharp reduction on "F" resources dependence? Is there a way to combine the representativeness of current milk production systems (i.e. 1% of G1, 17% of G2, 80% of G3, 1% of G4, and 1% of G5) in such a way that the overall "F" dependence is reduced to meet the characteristics of emergy matching alternative?

Decisions may lead to impact at larger scales, and time must be the target when sustainability issues are being taken into account, however, changing the established business as usual behavior of production systems management is not an easy task to accomplish, at least within brief periods. Thus, decisors usually consider not only indicators regarding environmental aspects, but also those related to economic ones, and this is discussed in the following section.

3.3.2. *Focusing on environmental upstream and economic impacts*

Considering that the EIR can, hypothetically, serve as a basis for the analyses of regional development plans (Odum, 1996), and that a value considered as sustainable tends to be that of the region where the production process is located (EIR of 0.75 in this study), results from simulation procedures are presented in Fig. 9. It shows a gradual sequence of the results obtained for the regional EIR, in reference to milk production in southern Minas Gerais. Fig. 9 shows that as EIR increases, a reduction in participation of the extensive system G3, along with an increase in the participation of semi-intensive systems G2 and G1, simultaneously occurs. The reason for this is the fact that the EIR establishes a relationship between inputs from the economy (F) and inputs from nature (I) and, in order to intensify milk production in conventional systems, the demand for external resources (F) is usually higher. With the increase in EIR comes the increase in participation of the more intensified systems, as well as a reduction in the participation of the extensive ones, which is exactly what the government envisages, by means of programs such as the "Minas Leite". As reported by Rótolo et al. (2012), a similar fact occurred in Argentina, where the local milk production underwent a production systems intensification process, which resulted in an increase in production, concomitantly with a reduction in number of producers. Authors observed this pattern as a worldwide tendency and argue that milk production sustainability can be as negatively affected as entire milk production-based regions.

It is worth noticing, in Fig. 9, that the calculated EIR closest to 0.75 is 1.50, with a distribution of the production systems that would result in the production of 392 million liters/yr, which is 57% lower than the current 911 million liters/yr production, approximately, with an EIR at 2.39. However, as the regional milk production EIR increases, so does the volume of milk produced, as a consequence of a wider participation of more intensified systems, thus resulting in higher productivity. According to Odum (1996), such concomitant increase in EIR and production occurs in a less efficient manner, as it causes an imbalance between the limiting factors "F" and "I". As a result, the regional milk production will feature low degrees of sustainability, as it will become more dependent on external resources, usually fossil fuel-based, prone to be avoided in a scenario featuring scarcity of such resource.

As usual, in several analyses based on sustainability indicators, finding a win-win option hardly happens due to a trade-off among the dimensions considered within them. In other words, the system that achieves a better environmental performance usually achieves, at the same time, a worse performance in economic indicators (see Agostinho and Ortega (2012) and Kocjancic et al. (2018), among others, about this issue); in this scenario, it seems clear that making decisions is not an easy task. Tools designed to support multicriteria-based decisions are available in the scientific literature, for instance, the analytical hierarchical process (AHP), as used by Oliveira et al. (2016) when assessing

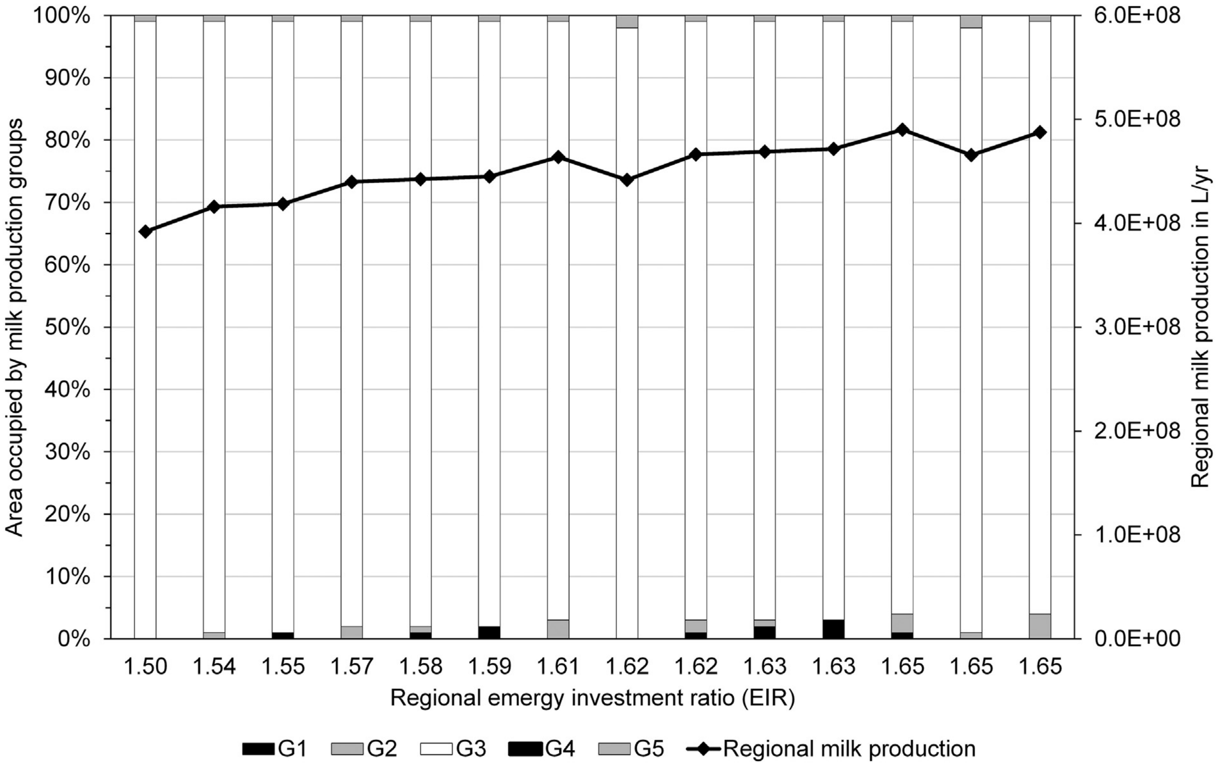

Fig. 9. Distribution of the milk production systems matching with EIR close to 1. The top 14 distributions from lower to higher EIR is presented, but the remaining 986 possibilities are provided in the Supplementary Material SM-G. Distribution of the milk production systems (represented in bars, in % of total regional area) must be read using the left vertical axis, while the resulting total milk production (represented by a line with dots, in L/yr) are read from the right vertical axis. The model relating milk production and the regional emergy investment ratio is L/yr = 8.0 E7 ln (EIR) + 2.0 E8 (with goodness of fit R^2 of 0.82).

the sustainability of milk production systems. However, most of those are subjectively based on weights provided by stakeholders. According to Odum and Odum (2008), all natural and human systems work under a pulsing behavior, which is divided into four main steps: growth, climax, degrowth and stabilization. This pattern tendency of resources exploitation, population and economic growth followed by ecological collapse was also reported by Tainter (1988) and Diamond (2005), when studying societal development over different periods. The pulsing occurs because systems are energy dependent, and the amount of available energy changes according to demand and sources availability. One of the main insights derived from the pulsing behavior is that policies (or growth patterns, life styles, decisions, and so on) for one specific phase cannot be efficient for the other ones. For instance, the business as usual as practiced in the growth phase cannot be a pattern for the degrowth phase (Murphy and Hall, 2011). Considering an analogy for the milk production, it becomes clear that a strategic plan focused on economic returns by supporting G4 or G5 milk production systems will hardly perpetuate during the degrowth phase characterized by lower availability of energy. This implies that, assuming our current societal development is located in the growth pulsing phase - nearly reaching the climax phase, as stated by energy analysts (Hallock Jr. et al., 2004, among others) -, the more efficient milk systems, despite their dependence on resources from the larger economy (basically fossil energy as by G1, G2, G4 and G5 system) should be promoted. On the other hand, the G3 system will be the target during the degrowth phase due to its lower demand of nonrenewable resources to produce milk, therefore sustaining itself during this phase of lower resources availability. Decisions must be sensitive to the pulsing pattern, as a support when establishing the most appropriate policies for each one of the different temporal ranges, according to the different pulsing phases. According to Odum and Odum (2008), society will necessarily face the degrowth phase, so appropriate plans must be developed to allow for a smooth passage between the pulsing phases.

Another important aspect that must be taken into account when supporting decisions is the one related to the external disturbances influencing milk production. Systems that are highly dependent on nonrenewable external resources are less resilient, and they could face serious problems in maintaining their operation in a scenario with negative pressures or drains acting against it (for instance, economic disturbances, lower resources availability, social issues as those related to human-labor availability or even market oscillation, and so on). Depending on the power of the external pressure (as, for example, the 2008 world economic crisis), production systems can even collapse. A regional diversity of production systems, with different scales of production and management, could be a strategy against negative pressures. To reach sustainability during the climax and/or degrowth pulsing phases, Brown and Ulgiati (2011) discuss the need for a paradigm change in production processes, emphasizing that business as usual can no longer be accepted. Key aspects to reach such change can derive from considering resource availability to represent real wealth rather than money, using net emergy as an important parameter for decisions, that production must go beyond quantity, and the existence of a consumption equity between the have and have-nots.

In an attempt to elaborate on a more appropriate distribution of milk production systems within the southern region of Minas Gerais State according to regional EIR matching criteria, this new scenario would result in an increase of the G3 system representativeness from 80% to 99%, whereas the G5 would remain at 1%, and all the others would be extinguished (Fig. 9; Supplementary Material SM-G). This new distribution will cause changes in both social-economic and environmental indices for the regional milk production. This alternative scenario predicts the highest level of sustainability, in accordance with the methodological approach utilized in this work, i.e. this scenario features an EIR at 1.50, the closest possible to that of southern Minas Gerais (0.75). However, how to adapt the alternative scenario to the population's demand for more milk, and the government's intention to technify the production systems? Enhancing the presence of family-producers with traditional extensive systems could be an alternative to increase the regional milk production sustainability, however, the pressure for higher production could impose the technification of these systems.

In this sense, a potential alternative could come from agroecology. The application of agro ecological principles in milk production, in order to reduce the dependence on external fluxes, and increase production while concerning about both animal and employees' welfare has obtained good social, economic, and environmental results (Cederberg and Mattsson, 2000; Muller-Lindenlauf et al., 2010; Teixeira, 2011; Kocjancic et al., 2018). These principles can be used by the family producers to help them reduce the dependence on external resources, while enhancing the system's profitability. Before doing so, those family producers need to be given technical information on these agro ecological principles, besides identifying economical advantages from adopting them. These systems were not assessed in this present study, however, they may be taken into consideration in future works, in order to aid in the proposal of sustainable alternatives for milk production in southern Minas Gerais.

4. Conclusions

According to data and methods used in this work, the main conclusions can be drawn as follows:

a) Cluster analysis showed the existence of five main different milk production systems (G1, G2, G3, G4 and G5) in the southern region of Minas Gerais state, by differing in productivity, handling, feed diet, infrastructure, and administrative control. Using this clustering approach is important when studying production systems within regions because it can provide higher accuracy on the sample considered as representative for the region under study.
b) Under an upstream perspective, emergy indicators show G3 as the one with the best environmental performance among all five milk production systems studied, as it features higher renewability (28%), makes more indigenous resources available to society through low investment from economic resources (EYR 1.72), higher effectiveness in driving regional development (EIR 1.39), lower environmental load (ELR 2.46), and higher sustainability degree (ESI 0.70) than the other groups. However, when considering the global efficiency – i.e., an output/input relationship in L_{milk}/sej – equally important for a decision as the upstream environmental loads, the G2 system should be promoted, followed by G1, G3, G5 and G4.
c) The regional perspective shows that increasing milk productivity as planned by the Brazilian governmental programs – such as the “Minas Leite” training program that aims to replace G3 with G2 milk production systems – will result in an overall increase of system's dependence on fossil-based resources. Although this plan will increase the volume of regional milk production (from 911 to 2821 million L_{milk}/yr), it will also result in an uneven emergy matching with EIR at about 6, representing a less efficient use of emergy. Attempting to increase the sustainability of milk production by optimizing the regional EIR will require an expansion of the G3 system above 95% in all milking areas, resulting in EIRs around 1.5, which reflects a more efficient use of emergy, however, the regional milk production will decrease by about 57% (from 911 million to 392 million L_{milk}/yr).

The existence of a trade-off between production (volume of milk produced) and environmental load or sustainability seems evident. Such economic-environmental binomial frequently rises on the floor of discussions towards societal development. A win-win scenario can hardly be found and decisions should consider the phases of societal development, according to the pulsing paradigm. In this context, the variable “time” is valuable and must be considered for supporting decisions, i.e. policies based exclusively on short-term goals should be replaced by policies focused on the different phases of development pulsing.

Besides diagnosing, and subsequently ranking the milk production systems according to their environmental performance, this work also provides important subsidies for decisors regarding a strategic plan towards a sustainable milk production under a regional perspective. We hope the methodological procedures adopted herein (for instance, using EIR to support discussions on alternatives for regional development, and the uncertainty analysis on the partial renewabilities and UEVs used) can be useful to emergy analysts in their further studies.

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Appendix A. Renewability fraction for each system input flows considered in this work

Item	Renewability fraction in %		Observation
	Lower value	Upper value	
Sun	100	100	By definition.
Rain	100	100	By definition.
Wind	100	100	By definition.
Underground water	50	85	Not fossil underground water. Assumed range according to author's estimation on the annual regional watershed charge volume.
Soil loss	0	0	By definition.
Diesel	0	0	*
Gasoline	0	0	*
Steel	0	0	*
Stainless steel	0	0	*
Lime	0	0	*
Nitrogen	0	0	*

Phosphorous	0	0	[*]
Potassium	0	0	[*]
Urea	0	0	[*]
Feed	0	0	[*]
Seed	0	0	[*]
Seedings	0	0	[*]
Electricity	68	68	About 80% of total electricity generated in Brazil comes from hydropower sources. Partial renewability of 68% from Brown and Ulgiati (2002).
Concrete	0	0	[*]
Direct labor (for G1, G2, G4 and G5 systems)	22	50	The emergy renewability index for Brazil in 2011 (22% from Giannetti et al., 2018b) is considered for the lower value of partial renewability, and the 50% from author's assumption for the upper value.
Direct labor (for G3 system)	22	90	The upper value of 90% is assumed because G3 uses family and local labor, with higher renewability degrees.
Brazilian emergy per money ratio in 2011	22	22	The emergy renewability index for Brazil in 2011 (22% from Giannetti et al., 2018b) used to represent the indirect labor embodied in services.

[*] Materials from economy were considered as fully non-renewable because the time scale of their production/formation is too large and out of the window of interest of this research.

Appendix B. Unit emergy values considered in this work within the Monte Carlo analysis

Item	Unit	Unit emergy values in sej/Unit				Observation
		Lower value	References	Upper value	References	
Sun	J	1.00E+00	Odum, 1996	1.00E+00	Odum, 1996	Reference value.
Rain	J	2.03E+04	Odum, 1996	2.31E+04	Odum, 1996	Rain (chemical; Gibbs free energy).
Wind	J	1.94E+03	Odum, 1996	1.94E+03	Odum, 1996	–
Underground water	g	1.81E+05	–	2.58E+05	–	Assumed as 25% higher and lower than the proposed value of Buenfil (2001).
Soil loss	J	9.80E+04	Odum, 1996	9.80E+04	Odum, 1996	Organic matter in the soil.
Diesel	J	1.07E+05	–	1.79E+05	–	Assumed as 25% higher and lower than the proposed value of Brown et al. (2011).
Gasoline	J	1.11E+05	–	1.85E+05	–	Assumed as 25% higher and lower than the proposed value of Brown et al. (2011).
Steel	g	2.92E+09	Bargigli and Ulgiati, 2003	5.48E+11	Brown and Buranakarn, 2003	–
Satinless steel	g	4.66E+09	–	8.77E+11	–	According to Boustead and Hancock (1979), satinaless steel requires about 60% more energy to be produced than regular steel. This percentage was assumed here in estimating the UEV for stainless steel.
Limestone	g	9.95E+08	–	1.66E+09	–	Assumed as 25% higher and lower than the proposed value of Odum (1996).
Nitrogen	g	5.56E+09	Odum, 1996	3.48E+10	Brandt-Williams, 2002	–
Phosphorous	g	4.58E+08	–	7.63E+08	–	Assumed as 25% higher and lower than the proposed value of Odum (1996).
Potassium	g	9.48E+08	–	1.58E+09	–	Assumed as 25% higher and lower than the proposed value of Odum (1996).
Urea	g	3.93E+09	–	6.54E+09	–	Assumed as 25% higher and lower than the proposed value of Odum and Odum (1983 apud Cuadra and Rydberg, 2006).
Corn feed	g	1.90E+09	Odum, 1996	1.03E+10	Brandt-Williams, 2002	–
Soybean	g	1.36E+09	Cavalett and Ortega, 2009	1.77E+09	–	For the upper value, it was assumed na increase in 30% on the lowe value according to authors knowledge of soybean production.
Seeds	g	2.35E+09	Fahd et al., 2012	2.55E+09	Bastianoni et al., 2008	–
Seedlings	g	8.37E+08	–	1.39E+09	–	Assumed as 25% higher and lower than the proposed value of Agostinho and Ortega (2012).
Electricity	J	1.16E+05	Giannetti et al., 2015	1.16E+05	Giannetti et al., 2015	–
Concrete	g	1.43E+09	–	2.39E+09	–	Assumed as 25% higher and lower than the proposed value of Buranakarn (1998).
Labor	h	5.70E+12	Brown and Ulgiati, 2004	2.20E+13	Kamp et al., 2016	UEV from Kamp et al. (2016) by assuming Brazilian B1 and B2 parameters as equal for Ghana in 2000; total emergy for Brazil in 2011 of 1.10E25 sej/yr (Giannetti et al., 2018b), 2.0E8 inhabitants.
Services	USD	4.26E+12	Giannetti et al., 2018b	4.26E+12	Giannetti et al., 2018b	Emergy accounting for Brazil in 2011.

Obs.: All UEVs refer to a global emergy budget of 12.1 E24 sej/yr (Brown and Ulgiati, 2016) and do not include labor and services.

Appendix C. Input flows for the five milk production systems evaluated[a]

Note	Item	Unit	Input flows in Unit/ha yr				
			G1	G2	G3	G4	G5
1	Sun	J	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13
2	Rain	J	8.00E+10	8.00E+10	8.00E+10	8.00E+10	8.00E+10
3	Wind	J	9.20E+09	9.20E+09	9.20E+09	9.20E+09	9.20E+09
4	Underground water	g	5.33E+07	4.20E+07	4.25E+06	1.05E+08	7.73E+07
5	Soil loss	J	2.01E+10	1.99E+10	2.88E+10	4.70E+10	3.20E+10
6	Diesel	J	5.14E+09	5.62E+09	1.85E+09	2.65E+10	1.37E+10

7	Gasoline	J	6.89E+07	0.00E+00	7.23E+08	0.00E+00	2.05E+09
8	Steel	g	1.53E+04	1.29E+04	1.96E+03	4.51E+04	2.85E+04
9	Stainless steel	g	7.44E+02	1.14E+03	0.00E+00	2.44E+03	1.00E+03
10	Lime	g	6.87E+05	1.47E+06	5.76E+04	1.36E+06	7.05E+05
11	Nitrogen	g	4.29E+04	3.37E+03	4.15E+03	1.99E+04	1.09E+05
12	Phosphorous	g	4.40E+04	1.18E+04	1.45E+04	6.97E+04	8.76E+04
13	Potassium	g	2.86E+04	6.74E+03	8.30E+03	3.98E+04	1.13E+05
14	Urea	g	1.37E+05	4.74E+05	3.46E+04	1.81E+05	2.01E+05
15	Feed						
	Corn	g	1.00E+06	3.18E+05	0.00E+00	5.48E+06	2.89E+06
	Soybean	g	8.21E+05	2.61E+05	0.00E+00	4.48E+06	2.36E+06
16	Seed	g	3.12E+04	2.11E+03	6.34E+03	1.99E+04	3.44E+04
17	Seedlings	g	0.00E+00	1.57E+05	0.00E+00	0.00E+00	0.00E+00
18	Electricity	J	4.30E+09	1.78E+09	4.77E+08	4.56E+09	8.27E+09
19	Concrete	g	1.16E+05	1.57E+05	1.36E+05	2.72E+05	1.94E+05
20	Direct labor	h	1.11E+02	3.07E+02	1.72E+02	4.76E+02	1.53E+02
21	Services	USD	1.74E+03	1.12E+03	5.45E+02	8.68E+03	4.72E+03

[a] Obs.: Detailed calculation procedures available in the Supplementary Material SM-B to SM-F.

Appendix D. Data used for a regional analysis

Parameter	Unit	Individual milk production systems					Regional analysis	
		G1	G2	G3	G4	G5	Current aerial distribution for milk production[a]	"Minas Leite" program[b]
R	E+15 sej/ha yr	1.74	1.74	1.74	1.75	1.75	–	–
N	E+15 sej/ha yr	1.97	1.95	2.82	4.61	3.14	–	–
Mr	E+15 sej/ha yr	0.34	0.14	0.04	0.36	0.65	–	–
Mn	E+15 sej/ha yr	15.70	12.20	1.57	61.70	36.90	–	–
Sr	E+15 sej/ha yr	2.18	2.58	1.37	10.50	5.18	–	–
Sn	E+15 sej/ha yr	6.76	6.44	3.34	33.00	17.00	–	–
F	E+15 sej/ha yr	24.98	21.36	6.32	105.56	59.73	–	–
Area[c]	%	1.00	17.00	80.00	1.00	1.00	100.00	100.00
Area	ha	5400.00	91,800.00	432,000.00	5400.00	5400.00	540,000.00	540,000.00
Production	L_{milk}/ha yr	5538.00	5054.00	634.00	16,822.00	9827.00	–	–
Production	million L_{milk}/yr	29.90	463.96	273.89	90.84	53.06	911.65	2821.09
R	E+15 sej/yr	–	–	–	–	–	939,708.00	939,708.00
N	E+15 sej/yr	–	–	–	–	–	1,449,738.00	1,073,898.00
F	E+15 sej/yr	–	–	–	–	–	5,717,660.40	12,216,366.00
EIR	dimensionless	–	–	–	–	–	2.39	6.07

[a] Current aerial distribution considers the current area for each individual milk production system.
[b] For the "Minas Leite" governmental program, the G3 system is totally replaced by G2.
[c] Percentage of representativeness in the total milk production area (540.000 ha) covered by Southern region of Minas Gerais State.

Appendix E. Calculation procedure for the aggregated emergy flows of Southern Region of Minas Gerais State

Renewables (R)

Only the highest one is considered, so as to avoid double accounting:

(i) Sun: solar radiation = 16 MJ/m^2/day; Albedo = 20%; Emergy flow = 16 MJ/m^2/day × 365 days/yr × (1–0.2) × 10,000 m^2/ha × 3,687,884 ha × 1 sej/J = 1.72E20 sej/yr

(ii) Rain: rainfall = 1.6 m^3/m^2/yr; Gibbs free energy = 5000 J/kg; Emergy flow = 1.6 m^3/m^2/yr × 5000 J/kg × 1000 kg/m^3 × 10,000 m^2/ha × 3,687,884 ha × 2.31E4 sej/J = 6.81E21 sej/yr

(iii) Wind: Air density = 1.3 kg/m^3; Average wind velocity = 4.7 m/s; Geotropic wind = 2.82 m/s; Drag coefficient = 0.001; Emergy flow = 1.3 kg/m^3 × (2.82 m/s)3 × 0.001 × 10,000 m^2/ha × 31.56E6 s/yr × 3,687,884 ha × 1.94E3 sej/J = 6.58E19 sej/yr

Nonrenewables (N)

Mineral extraction was disregarded because it is exported without use and contributes exclusively to Gross Domestic Product (GDP), not to total emergy (this same approach is suggested by Odum, 1996); Average value for soil loss (agricultural and natural areas) estimation based on official reports and personal communication with experts in the field = 6.45 ton/ha/yr; Emergy flow = 6.45 ton/ha/yr * 1000 kg/ton * 0.04 kg of organic matter (o.m.) /kg * 5400 kcal/kg(o.m.) *4186 J/kcal * 3,687,884 ha * 9.80E4 sej/J = 2.10E21 sej/yr

Feedback from economy (F)

Regional Gross Domestic Product (GDP) = 16,067 million USD/yr; Region's area = 14,239 miles^2; Income density = 1.13 million USD/miles^2/yr; Estimated "F" from Odum's monogram (Odum, 1996 p. 76) = 0.11 million USD/miles^2/yr; Emergy flow = 0.11E6 USD/miles^2/yr *4.26E12 sej/USD * 1/259 miles^2/ha * 3,687,884 ha = 6.67E21 sej/yr

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