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Emergy evaluation of grazing cattle in Argentina's Pampas

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Abstract

Argentina has a tradition of grazing livestock and the Pampas region produces 61% of the total beef cattle, with more than 80% allocated to internal consumption. Potential for expanding exports has created incentives for increasing production, yet national decisions should include an assessment of natural resources and environmental impacts of the grazing system. The aim of this study was to evaluate the complete system of grazing cattle in Argentina's Pampas in an environmental and economic context. Emergy analysis is used to assess the potential for long-term, sustainable cattle production including indicators of performance and environmental sustainability, with focus on all sources of input energy and the energy value of outputs. Rainfall contributes 61% of the total emergy to the grazing system. Natural pasture depends most highly on local renewable resources (85%) and less than 4% on purchased inputs. In contrast, sowed pasture and maize are 41 and 35% dependent on purchased inputs. Results showed the grazing system to be environmentally sustainable with a low impact on the environment. Yet specific subsystems where grazing cattle depend for part of the cycle on improved sowed pasture or on maize have a relatively high dependency on external inputs and moderate use of local non-renewable resources. Natural pastures have the highest environmental sustainability and the lowest load on the environment, due to low losses of soil organic matter. Appropriate management strategies are available for grazing livestock systems, yet government regulations need to provide incentives to ensure future production stability and economic returns while minimizing adverse effects on the environment. One method to achieve this is recognizing and rewarding farmers for the emergy contributions of the environment.

Keywords: Beef production; Pastures; Ruminant management; System evaluation; Production efficiency

1. Introduction

The sound management of natural resources and development of procedures for the integrated study of human and natural processes are among the most important and complex problems facing humanity (Brown et al., 1995). One large challenge is to include an assessment of natural resources and environmental impact during the evaluation of agricultural production activities. Neither the discipline of economics nor ecology alone adequately addresses the problems that world society currently faces (Brown et al., 1995). It has been difficult to deal with the consequences for nature and society with narrow disciplinary strategies and techniques. It is necessary to use a wider approach that combines biophysical and social methods and criteria, recognizing them as critical elements of the whole system (Brown et al., 1995; Ikerd, 2005).

Emergy analysis is an environmental accounting method based on a holistic systems concept, and includes tools to evaluate a system considering both nature and society, where human society is coupled and evolving within its natural context. Emergy is defined by Odum (1996) as the available energy of one kind that has already been used, directly or indirectly in each step, to make a product or provide a service. Emergy analysis was developed as a tool to inform

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environmental policies and to evaluate quality of energy resources in the dynamic of complex systems (Brown and Ulgiati, 1997). In agriculture, emergy analysis has been used in studying agroecosystem behavior as a whole. It has been applied in evaluation of the efficiency of resource use in different production systems (Andresen et al., 2000; Lagerberg, 2000; Beck et al., 2001; Bastianoni et al., 2001; Lefroy and Rydberg, 2003; Ortega et al., 2003; Martin et al., 2006). It has also been applied to evaluate different size and scales of equipment on farms such as traction from horses or tractors (Rydberg and Jansén, 2002) and the ecological integrity and ecosystem health (Campbell, 2000).

Livestock production is the world's largest user of land either directly through grazing or indirectly as a source of fodder and feed grains (Steinfeld, 2004). It is an important activity in sustainable agricultural practices linked to cultural traditions and an important food source. There is an expected growth in livestock production in developing countries as incomes rise and meat consumption increases.

Argentina is the fifth largest producer of cattle in the world, contributing 2.5 million tonnes or 4.7% of world production (FAO, 2002). Nearly all the cattle are raised through grazing, with only 1.2% finished in corrals (INDEC, 2002). A majority of the cattle slaughtered is consumed domestically, 87% in 2002 (FAO, 2002), although in recent years Argentina has been pushed to expand exports in fresh meat from cattle.

Grazing through the whole year produces meat with less cholesterol than the meat produced through feedlot (García et al., 1996). Opportunities for export meat produced through grazing are appealing to farmers and the government, and efforts to increase production have been growing (Latimori, 2004). Several studies examined the use and management of natural resources through grazing with minimal external inputs, assessing productivity, profitability and/or sustainability. Examples include analysis of use of specific natural resources (García and Santini, 1996; Agnusdei et al., 2001), efficiency of fossil energy use (Gingins and Viglizzo, 1981), environmental impacts (Viglizzo and Roberto, 1997; Viglizzo et al., 2001), or production stability (Viglizzo and Roberto, 1985).

This study was designed to evaluate the grazing cattle system in Argentina's Pampas within the region's environmental and economic context. Emergy analysis is used to assess the environmental support for cattle production and then calculate indicators of performance and environmental sustainability. This analysis provides an insight on what factors are important to maintain the current system and what practices should be modified. We also provide results that indicate why decision makers should seek strategies to recognize ecosystem services and ensure the future economic welfare and environmental integrity of the region.

2. Materials and methods

2.1. Study location and grazing system

The complete cycle of grazing cattle for meat production in Argentina's Pampas Region was chosen for study. The Pampas, in the central-eastern region, produces 61% of the beef cattle in Argentina and includes 65% of the farms dedicated to livestock, of which 35% run the complete production cycle (SENASA, 2002).

2.1.1. Climate, soils, and vegetation

Rainfall ranges from 1200 mm $year^{-1}$ in the eastern part to 500 mm $year^{-1}$ in the west (Garbulsky and Deregibus, 2004). The region enjoys a temperate climate, where autumn and spring are rainy but there is often lack of rain during summer (Castaño, 2003). The average temperatures are from 6 to 10 °C in winter to 21 to 26 °C in summer, thus there are 60–120 days where forage production is very low (Castaño, 2003). Soils are mainly Molisols, with a deep accumulation of loose, windblown materials (loess), resting upon granite and other ancient crystalline rock, mostly free of stones (Soriano, 1992). The land is flat with some undulations in the northeast, some hills in the southeast, and a big depression in the Salado river basin (Soriano, 1992). The vegetation structure corresponds to a prairie in humid years and to a pseudo-steppe during dry periods, but autochthonous species have been substituted by meadow and crops (Soriano, 1992; Ruiz et al., 2000).

2.1.2. Grazing system

The study system was the livestock component within an 11-year rotation of mixed production (6 years cropping–5 years livestock) as shown in Fig. 1. The prototype system for study was a farm that had a size of 500 ha, average for the Pampas Region (INDEC, 2002). On this farm, 300 ha are sowed in cropping each year and 40 ha sowed to annual pasture or winter cereal for grazing. As the focus of attention for this study is cattle for meat production, cereal grain for sale is not considered as an output of the system, but the maize (*Zea maize* L.) subsystem was evaluated since it is a feed for the animals.

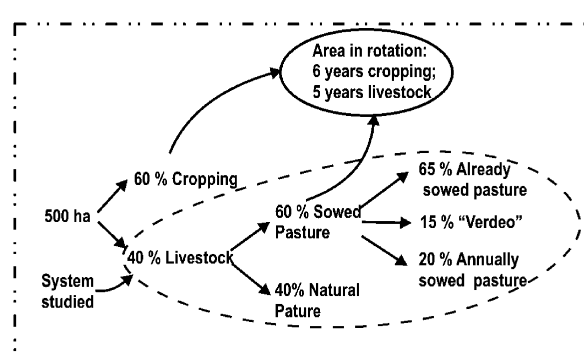

Fig. 1. Overview of land utilization system with grazing cattle and cropping system (*verdeo* refers to cattle grazing cereals in winter).

The carrying capacity assumed for the study was 1.5 EV ha^{-1} $year^{-1}$ (G. Bavera, personal communication, 2005) where 1 EV (*equivalente vaca* or animal unit) is the requirements of a cow weighing 400 kg which produces and raises a calf until weaning at 160 kg (including the hay for the calf); it is also equivalent to a steer (410 kg) that puts on weight at an average of 500 g d^{-1} (Cocimano, 1975). It was assumed that 1 AU ha^{-1} $year^{-1}$ was included in the cow–calf operation and 0.5 AU ha^{-1} $year^{-1}$ for feedlot wintering-fattening (Lange, 1978). It was assumed that 80% of calves reached weaning, approximately 12 months was used for wintering-fattening, that bulls account for 4–5% of the breeding herd, that approximately 20% of cows are replaced annually (Carrillo, 1997), and that cattle drink 55 l d^{-1} of water (G. Bavera, personal communication, 2005). Other production details and assumptions are found in Rótolo (2005).

Cattle were grazed on pasture through the whole year. In addition, annual winter cereal was grazed in the vegetative stage, a subsystem named *verdeo*, and hay reserves were used when sowed and natural pastures had inadequate production. Maize grain is utilized as a supplementation for fattening during 90–120 days. Thus, natural pasture was the principal feed for cow–calf operations, accounting for approximately 80% of the feed requirements in terms of metabolizable energy. Hay and maize stubble accounted for around 10% each in the model system. Cattle grazed in a rotational pattern. Horses are utilized to manage the herd and it was assumed that they were fed with sowed pasture.

Animals that were finished on grain were fed on sowed pasture (70% of the requirements), *verdeo* (20%), hay (5%), and maize stubble (5%), and supplemented with 120 kg $animal^{-1}$ $year^{-1}$ of maize grain to increase and accelerate the fattening process.

Natural pasture was analyzed without fertilization or inter-sown forage species. Hay production from 10% of the pasture as spring surplus grass was also evaluated. Improved pasture was analyzed as a mixture of grasses and legumes with N and P fertilization at sowing time and annual N fertilization afterwards (Castaño, 2003). As the pasture lasted 5 years, approximately one-fifth is sowed annually. Calculations for fuel, seeds, P fertilization, and machinery for ploughing and sowing were based on the area that is sowed annually. Agrochemicals and N fertilization were evaluated for the whole area occupied by sowed pasture. Approximately, 30% of spring production was utilized for making hay. It was assumed that cattle harvest approximately 65% of the production, since the other 35% is needed for pasture regrowth (García and Santini, 1996). The yield of *verdeo* is referred to as harvested production.

Maize was sowed without tillage and the harvest was contracted. The proportional part of maize land allocated to cattle was calculated, and also the proportional part of the grain utilized for animals since their grain requirements are low. Grain and stubble are considered as coproducts in the emergy evaluation. Thus, only the emergy for grain was accounted for in the final evaluation because it carries the largest emergy flow. Adding the emergy for stubble would be double counting of emergy.

Due to the rotation strategies, the investments for infrastructure were planned for the whole area, but evaluated in the subsystem where they contributed. For example, buildings for machinery were accounted for in each primary production subsystem, and wood for fences only in the livestock area.

Erosion rates range from 2 t ha^{-1} $year^{-1}$ in natural pasture to 10 t ha^{-1} $year^{-1}$ for *verdeo* or sowed pasture (Viglizzo, personal communication, 2005), but in this last case we calculated the proportion of erosion based on a rotation of 11 years, which represents 5.45 t ha^{-1} $year^{-1}$; in contrast, maize is 8 t ha^{-1} $year^{-1}$ (Michelena et al., 1989).

The output of the system is live animals (surplus of heifers, steers, cows and bulls replaced annually) ready for slaughter. The annual production of the system was estimated at 252 kg ha^{-1}. The animals leave the farm with an estimated live weight of 400 kg $animal^{-1}$, since the predominant breed for finishing found in the region is Aberdeen Angus.

2.2. Methods

2.2.1. Emergy analysis—general

Emergy analysis is a quantitative evaluation technique that determines the amount of direct and indirect energy of

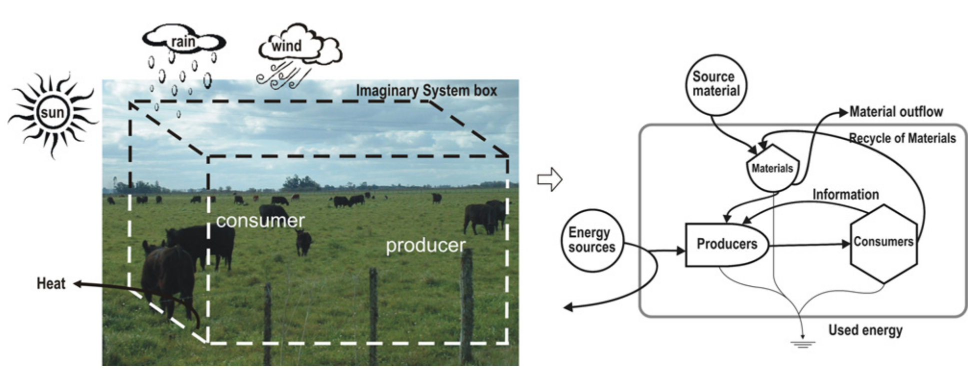

Fig. 2. Defining a system. (a) Setting the window of attention, example of mental box placed around a system. (b) Window of attention shown in energy system diagram (adapted from Odum and Odum, 2001).

one kind that has been used during a certain process to generate resources, services and products of different quality (Odum, 1996). It is a universal measure of the work of nature and society converted to common units. It is based on general systems theory and systems ecology (Odum, 1983), and it measures complexity and transformations, self-regulation, and emergent properties—when the whole is different from the sum of its parts (Wilson and Morren, 1990). In an emergy study system diagrams of processes are drawn to organize evaluations and account for all inputs and outflows from processes. An energy system language (Odum, 1983; Brown, 2004) is utilized to picture the driving forces of the system and the interactions that occur within it. Odum's systems language is a macroscope that forces one to overview and diagram the system, the relationships between components, and to think process (Brown, 2004). An emergy evaluation characterizes systems by the flow of energy, material and information (Fig. 2). Each symbol has a meaning, for example, the bullet represents ‘‘production''; the hexagon, ‘‘consumer''; the tank, ‘‘storage''. A complete description of the symbols can be found in (Odum, 1983, 1996). Energy is transformed, material is recycled and performs different kinds of work, and different kinds of energy are not equal in their contributions to processes (Odum and Odum, 1981; Odum, 1996). When accounting for different forms of energies that have contributed to a process or service, they must be related to units of one kind of energy (Odum, 1996). For convenience all forms of energies are expressed in solar energy terms (Odum, 1996). The accumulated amount of these energies used up in the chain behind a good or services denotes its emergy value and it is counted as solar emergy joules, abbreviated sej, which actually is the available energy of one kind consumed in transformations. Unit emergy values (also called emergy intensities, or usually referred to as ‘‘transformity'') are calculated based on the emergy required to generate one unit of product. The higher the hierarchical level of a product in the system or the more energy transformations, the higher the transformity.

According to Odum (1987) and Odum and Odum (2001), all systems appear to develop the same hierarchical emergy pattern. This is illustrated by the grass–cattle subsystems shown in Fig. 2, and a general diagram in Fig. 3. Part of the energy still flows back to lower units to reinforce the system (Fig. 3c and d), an attempt to maximize the efficiency of the system. Units at different hierarchical positions are coupled in the system (producers with consumers) and the coupled units pulse over time following a process of growing, climax, and descent. The magnitude of the pulse depends on the hierarchical position in the system (Fig. 3g). For a fuller explanation of the theory and the methodology see Odum (1987, 1996). Brown and Herendeen (1996) and Haw and Bakshi (2004) enrich the concepts analyzing differences and similarities between embodied energy analysis and emergy analysis in the former and discussion of applications of emergy analysis in the latter.

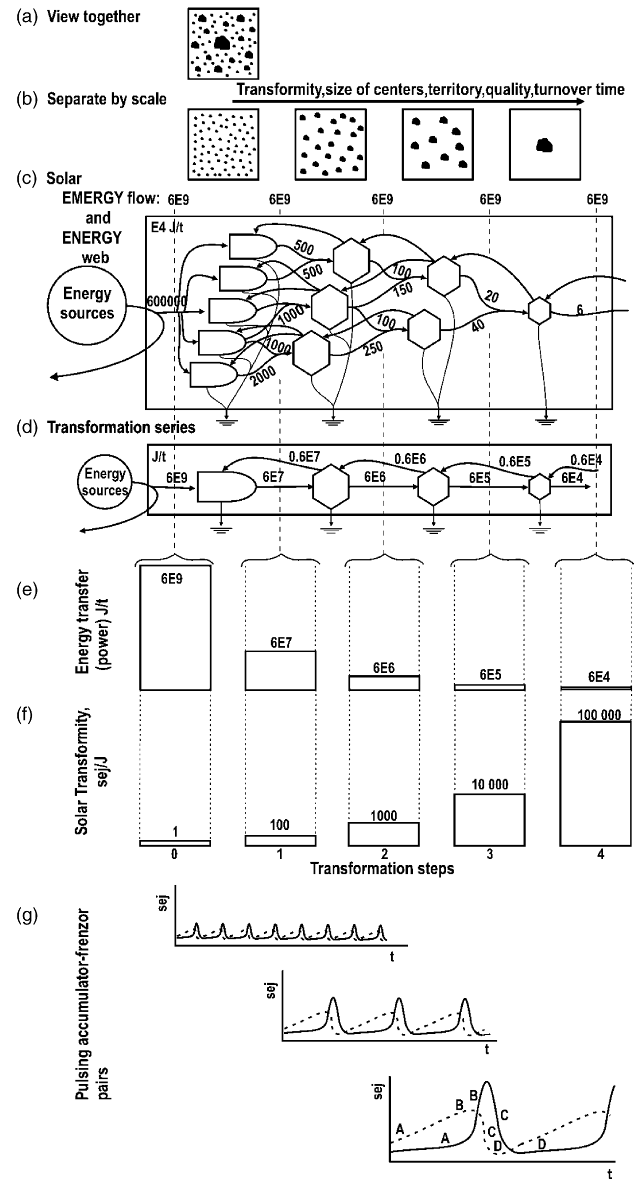

Fig. 3. Energy transformation hierarchy and pulsing units. (a) All units viewed together; (b) units separated by scales; (c) the units as a web of energy flows; (d) units shown as a transformation series with values of energy flow on pathways; (e) useful power flowing between transformations; (f) transformities; (g) pulsing pairs of producer (- - -) and consumer (—) with A = growth or exploitation, B = climax, C = descent or destruction, D = reset or renewal (adapted from Brown and Ulgiati, 2004; Odum, 1996; Campbell, 2000).

2.2.2. Data sources

The study system was chosen because of the importance of grazing and the availability of statistical data from public institutions in Argentina, such as the National Institute of Statistics and Census (INDEC) and National Service of Animal Health (SENASA). Data also came from international and foreign organizations such as Food and Agricultural Organization (FAO) and from local technical reports. Flows driving the studied system were expressed in physical units utilizing data from technical reports, National

University of Buenos Aires tables, and Monthly Agricultural Reports and converted into joules (J), grams (g), or monetary units (US$). Environmental data were obtained from National Meteorological Services of the Argentinean Air Force and Secretariat of Energy. Data for the infrastructure, machinery, soil organic matter, the herd, the feed, goods and management were taken from various authors, technical papers and reports prepared by the National Institute of Agricultural Technology (INTA), the Secretariat of Agriculture, Livestock, Fisheries and Food (SAGPyA), national and foreign universities, and agricultural input companies.

Final carrying capacity and details on feed and herd management were defined through personal communication with specialists in the field. Energy raw data for direct labor for feed subsystems was estimated from technical papers based on the hours that a worker spends on maintenance or for inspection; meanwhile data about salary was embedded into machinery services, except for natural pasture which was done with a proportional estimate of labor for inspection (INDEC, 1996). Regarding the herd, energy raw data for direct labor was also estimated from technical papers based on the hours that a

Table 1
Emergy table of grazing cattle for meat production

Note	Item (unit)	Data[b] (unit year^{-1} ha^{-1})	Emergy per unit[a] (sej unit^{-1})	Emergy (E+12 sej ha^{-1} year^{-1})	% Total emergy
Renewable resources (*R*)					
1	Sun radiation (J)	4.67E+13	1.00E+00[(a)]	46.72	3.95
2	Rain chemical energy (J)	3.95E+10	1.82E+04[(a)]	719.22	60.77
3	Wind kinetic energy (J)	2.46E+07	1.50E+03[(b)]	0.04	0.00
4	Earth cycle (J)	1.00E+10	3.44E+04[(a)]	343.77	29.04
5	Groundwater (J)	1.50E+08	2.99E+05[(c)]	44.63	3.77
Sum renewable (2 + 5)				763.86	64.54
Non-renewable resources (NR)					
6	Net top soil loss pasture (J)	8.55E+08	7.40E+04[(a)]	63.28	5.35
7	Net top soil loss nat. pasture (J)	2.46E+08	7.40E+04[(a)]	18.20	1.54
8	Net top soil loss *verdeo*, maize (J)	2.88E+08	7.40E+04[(a)]	21.30	1.80
Sum free inputs (R + NR)				866.63	
Purchased inputs (*P*)					
9	Gasoil and lubricants (J)	4.28E+08	6.60E+04[(a)]	28.23	2.38
10	Seeds of pasture (J)	1.54E+07	2.26E+05[(d)]	3.49	0.30
11	Seeds of *verdeo* (J)	6.01E+07	1.32E+05[(e)]	7.94	0.67
12	Seeds of maize (J)	6.61E+05	1.82E+04[(d)]	0.01	0.00
13	N fertilizer (g)	7.98E+03	9.54E+09[(e)]	76.17	6.44
14	P fertilizer (g)	5.69E+02	8.70E+09[(e)]	4.95	0.42
15	Agrochemicals (J)	3.20E+05	6.60E+04[(a)]	0.02	0.00
16	Machinery (g)	4.84E+02	1.13E+10[(f)]	5.44	0.46
17	Building steel (machinery, horse) (t)	1.51E−03	1.78E+15[(a)]	2.67	0.22
18	Building horse—concrete (g)	6.33E+02	1.54E+09[(g)]	0.97	0.08
19	Mineral supplements (g)	2.74E+04	2.46E+09[(h)]	67.34	5.69
20	Horse replacement (J)	3.21E+06	1.43E+05[(d)]	0.46	0.04
21	Bull replacement (J)	3.15E+07	1.07E+06[(d)]	33.71	2.85
22	Wood for sleeve, corrals, fences (J)	5.30E+07	3.11E+04[(i)]	1.65	0.14
23	Wire for corrals and fences (t)	3.30E−04	1.78E+15[(a)]	0.59	0.05
24	Mill and Australian tank (t)	1.28E−04	1.78E+15[(a)]	0.22	0.02
25	Drinking trough and bath (g)	3.60E+03	1.54E+09[(g)]	5.54	0.47
Sum purchased inputs (P)				239.44	20.23
Labor and services (*S*)					
26	Direct labor (J)	7.09E+00	1.68E+12[(j)]	11.90	1.01
27	Infrastructure, goods, health (US$)	30.78	1.94E+12[(j)]	59.72	5.05
28	Bull and horse (US$)	3.04	1.94E+12[(j)]	5.89	0.50
Sum (*P* + *S*)				316.19	
Output (*Y*)					
29	Fatted cattle (living weight average) (J)	2.67E+09	4.43E+05	1182.83	100.00
30	Fatted cow rep. (living weight) (J)	6.85E+08	1.73E+06	1182.83	100.00

[a] Emergy per unit (sej unit^{-1}) from: (a) Odum (1996); (b) Kangas (2002); (c) Buenfil (2000); (d) this study; (e) Brandt-Williams (2002); (f) Fugaro et al. (2003); (g) Brown and Buranakarn (2003); (h) Odum (2000); (i) Doherty (1995); (j) Ferreyra (2001).

[b] Details for specific raw values calculations can be found on a web site (http://www.inta.gov.ar/oliveros/info/documentos/Appendix.pdf).

worker spends with animals and the salaries accounted for the proportional part that workers spend with the head (INDEC, 1996); data for health and other services were estimated from literature. Prices were obtained mainly from year 2002 and some from 2005 from Monthly Agricultural Reports such as *Agromercado* and *Márgenes Agropecuarios*, as well as other web sources. Real prices on a 1996 basis (INDEC) were used in order to correspond to the national analysis performed for that year by Ferreyra (2001). Details for specific raw values calculations of each item can be found on a web site (www.inta.gov.ar/oliveros/info/documentos/Appendix.pdf).

2.2.3. Emergy analysis of the case study

The case study emergy evaluation follows the procedure suggested by Odum (1996). Emergy accounting is organized as a top down approach, where a diagram pictures all inputs and outputs of the complete cycle system. Narrowing the focus, natural pasture, sowed pasture, *verdeo*, maize, cow–calf operation, wintering-fattening and horse subsystems were analyzed and tables were constructed. Details of the conversions and analyses all can be found in Rótolo (2005) and on a web site (www.inta.gov.ar/oliveros/info/documentos/Appendix.pdf).

The emergy evaluation tables include rows that describe the inputs, organized into categories of local renewable resources, local non-renewable resources, purchased inputs, and labor and services. Outputs are shown in rows with fatted cattle and fatted cull cows. Columns in Table 1 show the raw values units (in unit ha^{-1} $year^{-1}$), emergy per unit (transformity, specific emergy and emergy per unit money, in sej $unit^{-1}$) and emergy (in sej ha^{-1} $year^{-1}$). Values of emergy per unit taken from past studies were adjusted to 1996 global emergy baseline of reference (from 9.44E+24 sej $year^{-1}$). The emergy per unit for labor and services was based on the emergy $person^{-1}$ ratio and emergy $money^{-1}$ ratio that was reported for the economy of Argentina during 1996 (Ferreyra, 2001). Outputs that are coproducts such as sun, rain, wind and earth cycles, or steers and culled cows, or grain and stubble, carry the same emergy content because they are products of the same sources, and one is a consequence of the others. For example, the main geobiospheric process of the earth contributes several inputs such as sun, wind, rain, waves, and earth cycle, to each area of the earth, and the emergy required for each is the same since they are coproducts of each other (Odum, 1996, p. 52). However, different transformities are used because the items differ, but in the final evaluation the one that should be used is the one that carries the largest emergy to avoid double counting. In our study we have calculated the contributions of sun, wind, rain and earth cycles (represented by the contribution of the rain emergy) over 1 ha of the Pampas region, although groundwater feeds our system from a bigger area where the land receives other contributions from renewable sources. For that reason in our calculations of renewable resources we add groundwater to rain, which carries the largest renewable emergy in our system. A more complete description of the procedure can be found in H.T. Odum's book *Environmental Accounting* (1996).

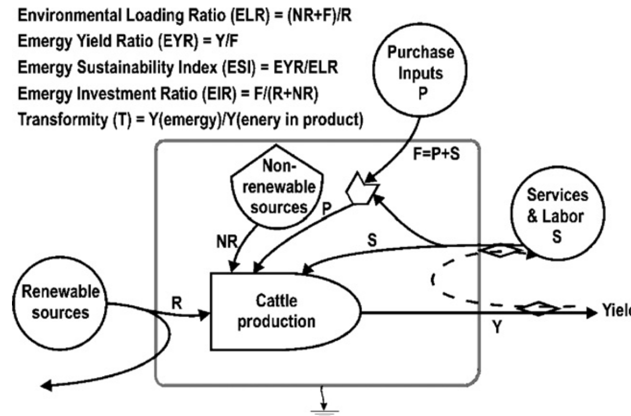

Fig. 4. Driving forces for the subsystems and the system focus of this study. Y = Total emergy; R = renewable sources; NR = non-renewable sources; P = purchased goods; S = labor and services; F = sum of imported emergy ($P + S$) (adapted from Lefroy and Rydberg, 2003).

2.2.4. Calculation of Indices

The final step is widening the view again, calculating emergy indices that relate emergy flows of the economy with those of the environment, and prediction of economic viability, carrying capacity, or fitness (Brown et al., 2000). The indices used in this study complement each other and are briefly described here; Fig. 4 shows the relationships among components and summarizes the indices and formulas.

- Environmental loading ratio (ELR) = (NR + F)/R. Relates non-renewable resources and imported emergy to local renewable ones. This index was used to calculate how much ''pressure'' is placed on the local environment by the entire grazing system and the subsystems (Brown and Ulgiati, 1997).
- Emergy yield ratio (EYR) = (R + NR + F)/F = Y/F. The ratio of the emergy of the output divided by the emergy of those inputs to the process (F = P + S) that are fed back from outside the system (Brown and Ulgiati, 1997). EYR was used to estimate process dependency on purchased inputs, and to show the local natural capital contribution to the region's economy. The ELR index complements the value of EYR since a value of EYR (Y/F = (R + NR + F)/F) could be high because of high R and low NR or vice versa (Brown and Ulgiati, 1997).
- Emergy sustainable indices (ESI) = EYR/ELR. This is a measure of economic (large yield) and environmental (low stress) compatibility (Ulgiati and Brown, 1998). Therefore, the best relation is to have the highest yield ratio with the lowest environmental load.

- Emergy investment ratio (EIR) = $F/(R + NR)$. This index measures the intensity of the economic development and the loading from the environment (Odum, 1996). It indicates whether the economic-environmental use made by a process is economically competitive compared with the EIR's of other alternative investments within the same economy.
- Emergy per unit (T) = Y(emergy in sej)/Y(g, J, \$). Transformity is defined as the emergy input per unit energy output (sej J^{-1}). Specific emergy is defined as the emergy per unit mass (sej g^{-1}). Emergy per unit money is defined as the emergy supporting of one unit of economic product (sej US$\$^{-1}$). Emergy per unit measures the emergy needed to obtain one unit of product. It also indicates the hierarchical position of a subsystem within the system. From now on, for convenience, the emergy per unit is referred to as transformity. Transformities of sowed pasture, hay from sowed pasture, natural pasture, hay from natural pasture, *verdeo*, maize grain, maize stubble, horse and cow replacement, calves to be fattened, wintered-fattened steers and fattened cow replacement were calculated (Rótolo, 2005; www.inta.gov.ar/oliveros/info/documentos/Appendix.pdf). Transformities from other authors have also been used and it was not able in same cases to avoid double counting with regard to services. However, this does not affect conclusions since the whole study is done on the same base and as far as we can predict them.
- Empower: The emergy value of a flow of energy per unit time, expressed as sej $time^{-1}$.

3. Results

3.1. Emergy evaluation of the grazing cattle system

An overview of the complete cycle of grazing cattle for meat production in Fig. 5, quantified in energy system language, which illustrates major interactions within the system as well as the main flows from nature and society that are driving system function. This is a visual version with data based on the emergy accounting of the system in Table 1. Rain was the largest renewable resource into the system, representing 61% of the total emergy. Groundwater added another 3.8%. Soil was lost and accounted for as much as 8.6%. The largest soil loss was from sowed pasture. Among purchased inputs minerals and fertilizers are the items with the most emergy requirements followed by bull replacement and fuel (gasoil + oil). Labor and services added almost 6.5% to the total. Transformities for fattened steers and fattened culled cows were 4.43E+05 and 1.73E+06 sej J^{-1}, respectively.

3.2. Emergy evaluation of the grazing cattle subsystems

To analyze and synthesize information from the system to arrive at the data shown in Table 1 and Fig. 5, it was necessary to quantify the contributions of nature and society to the different subsystems involved in the grazing cattle enterprise (Rótolo, 2005). Table 2 summarizes the main environmental and economic emergy flows that drive the different subsystems as well as the overall system. The values are expressed in sej ha^{-1} $year^{-1}$ and in % of the total

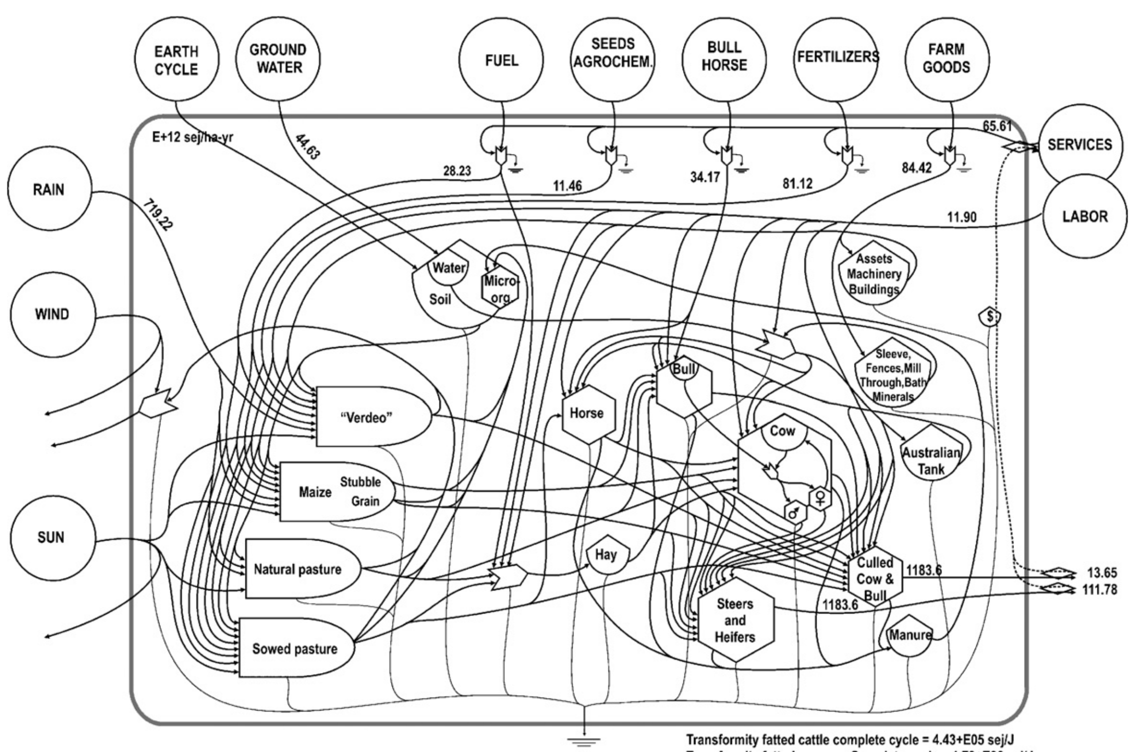

Fig. 5. Diagram of grazing cattle for meat production in energy language.

Table 2
Environmental and economic forces driving the subsystems expressed in emergy terms (sej ha^{-1} $year^{-1}$) as well as percentages of contribution to output *Y*

Subsystems and system	Outputs from the sub/system	Driving forces								
		Local renewable (*R*)		Local non-renewable (NR)		Purchased inputs (*P*)		Labor and services (*S*)		Yield (*Y*)
		E+14 sej ha^{-1} $year^{-1}$	% of *Y*	E+14 sej ha^{-1} $year^{-1}$	% of *Y*	E+14 sej ha^{-1} $year^{-1}$	% of *Y*	E+14 sej ha^{-1} $year^{-1}$	% of *Y*	E+14 sej ha^{-1} $year^{-1}$
Sowed pasture subsystem	Pasture	7.19	37.98	3.10	16.38	7.80	41.20	0.84	4.43	18.94
	Hay pasture	7.19	36.70	3.10	15.83	8.34	42.54	0.97	4.93	19.60
Natural pasture subsystem	Natural pasture	7.19	85.28	1.14	13.49	0.00	0.00	0.10	1.24	8.43
	Hay natural pasture	7.19	81.22	1.14	12.84	0.33	3.70	0.20	2.24	8.86
Verdeo subsystem	*Verdeo*	7.19	34.19	5.69	27.03	6.88	32.71	1.28	6.06	21.04
Maize subsystem	Grain	7.19	29.68	4.55	18.78	8.55	35.29	3.94	16.25	24.23
	Stubble	7.19	29.68	4.55	18.78	8.55	35.29	3.94	16.25	24.23
Cow–calf operation subsystem	Calves	8.56	68.25	2.09	16.66	1.24	9.92	0.65	5.17	12.54
	Cow R[a]	8.56	68.25	2.09	16.66	1.24	9.92	0.65	5.17	12.54
Wintering-fattening subsystem	Fat. steers	7.34	66.09	1.05	9.43	2.29	20.60	0.43	3.88	11.11
	Fat. cow R[a]	7.34	66.09	1.05	9.43	2.29	20.60	0.43	3.88	11.11
Horse subsystem	Horse	7.41	60.50	0.82	6.70	2.28	18.63	1.73	14.17	12.24
Complete cycle system	Steers	7.64	64.54	1.03	8.68	2.39	20.23	0.78	6.55	11.84
	Cow R[a]	7.64	64.54	1.03	8.68	2.39	20.23	0.78	6.55	11.84

[a] Cow *R*: cow replacement.

emergy for each subsystem. These calculations for the subsystems provide not only the emergy per unit values that were used in the analysis of the whole systems, but also to compare their contributions and thus identify where efficiencies could be improved.

The last rows in Table 2 show that the whole system (complete cycle or CC) had lower emergy requirements from soil organic matter (NR = 8.7%) than cow–calf operation and wintering-fattening operations studied separately. This is because each subsystem was analyzed per ha, but in the complete system all subsystems were present in 1 ha, thus it was necessary to quantify the proportion of land in each activity. In this way, it is possible to individualize the proportion of every flow contributed in the output of each subsystem, and identify emergent properties of the complete system. For example, natural pasture was the subsystem with the highest emergy requirement of local renewable resources (81–85%), and the lowest dependency on emergy coming from purchased inputs (0.0–3.7%). In contrast, sowed pasture with 41–43% followed by maize with 35%, were the subsystems with the highest emergy requirement from purchased inputs. *Verdeo* was the subsystem with the highest emergy requirements from local non-renewable resources (soil organic matter). Using Fig. 4 as reference and data from Table 2, emergy indices for each subsystem and for the complete cycle were obtained and they are presented in Table 3.

Emergy indices indicated that the complete cycle had higher emergy yield ratio (EYR = 3.73) than environmental loading ratio (ELR = 0.55), with a relatively higher contribution from renewable than from non-renewable and outside inputs. This result indicates a high local renewable natural capital contribution to the final output with a low environmental impact and a relatively high emergy sustainability index (ESI = 6.80).

As shown in Table 3, transformities for individual subsystems are very different, reflecting the different emergy qualities of the outputs and their position in the system. Culled cows ready to be slaughtered have a high transformity, while steers also ready to be slaughtered carried a significantly lower transformity. Cows cannot be completely replaced annually as with steers because they need time and energy to mature as breeding animals. Thus they carry a high transformity at the time of slaughter. Since the system depends on reinforcing resources to operate at optimum efficiency, further studies comparing the emergy requirements through an emergy analysis of only one cow–calf with only one cull cow could determine their position in the systems and if cull cows are leaving the system at the appropriate moment. We could determine which would be the most efficient and profitable step for these animals that, when the whole herd dynamics are considered, have high transformity and low energy content. Emergy investment

Table 3
Emergy indices for each subsystem and for the entire cattle grazing system

Subsystems and system	Output from the sub/systems	EYR[a]	ELR[a]	ESI[a]	T[a]	EIR[a]
		(Y/F)	((NR + F)/R)	(EYR/ELR)	YE/Ye (E+5)	($F/(R$ + NR))
Sowed pasture subsystem	Grass-pasture	2.19	1.63	1.34	0.15	0.84
	Hay pasture	2.11	1.72	1.22	2.13	0.90
Natural pasture subsystem	Grass-natural pasture	80.70	0.17	468.00	0.16	0.01
	Hay natural pasture	16.83	0.23	73.00	3.56	0.06
Verdeo subsystem	*Verdeo*	2.58	1.92	1.34	0.63	0.63
Maize subsystem	Maize	1.94	2.37	0.82	0.18	1.06
	Stubble	1.94	2.37	0.82	0.44	1.06
Cow–calf operation subsystem	Calves	6.63	0.47	14.20	11.70	0.18
	Cow rep.	6.63	0.47	14.20	20.20	0.18
Wintering-fattening subsystem	Fat. steers	4.08	0.51	7.96	4.16	0.32
	Fat. cow rep.	4.08	0.51	7.96	16.20	0.32
Horse subsystem	Horse	3.05	0.65	4.67	1.53	0.49
Complete cycle (CC) system	Steers CC	3.73	0.55	6.80	4.43	0.37
	Cow CC	3.73	0.55	6.80	17.28	0.37

[a] EYR (emergy yield ratio); ELR (environmental loading ratio); ESI (emergy sustainability index); T (emergy per unit (sej J^{-1})), all from this study; EIR (emergy investment ratio).

ratio of the system (EIR) was 0.37, which in general means that the relatively high free environmental contribution to society is feasible with relatively low investments from the economy. The analysis showed also that those free environmental resources lean more on renewable than on non-renewable resources (Table 2).

An overview of the complete system performance, and examination of the performance of its subsystems in Table 3, shows that natural pasture had by far the highest ESI among the subsystems. This subsystem received very few inputs from the economy outside the farm, so they carried the highest EYR. It was also the subsystem with the lowest ELR because local renewable contribution is much higher than local non-renewable resources (soil organic matter). Sowed pasture and *verdeo* subsystems showed higher EYR than ELR, indicating a higher contribution from local natural capital to the final output. Sowed pasture has a lower EYR and higher ELR than *verdeo* due to a higher contribution from outside inputs. The transformity of sowed pasture was the lowest among the subsystems. Transformities of hay from sowed and natural pasture were two of the largest among primary production factors and higher than horse transformity.

Regarding the outputs from cow–calf and wintering-fattening subsystems, culled cow (from cow–calf operation) carried the highest transformity showing the highest emergy quality of these reproductive animals. Fattened steers (from wintering-fattening subsystem) carried the lowest transformity among secondary production. Horses also had high EYR, low ELR and therefore high ESI and performed well within the system. The results showed that horses had lower EYR and higher ELR than cow–calf operation and wintering-fattening subsystem, but they were very minor elements in the overall system as shown in Table 1.

4. Discussion

The grazing cattle system in the Pampas showed high ESI (6.80), low ELR (0.55) and low EIR (0.37), compared to other systems reported in most literature (Table 4). An exception is the indigenous Maya agroecosystem of Chiapas (Mexico), which cycles through three stages and polyculture is used in each stage, obtaining a multiple kind of primary production outputs—corn, fruits, vegetables (Martin et al., 2006). The low ELR (0.55) and high EYR (3.73) in the Pampas grazing system were due to high dependence on local renewable resources, accounting for 65% (Tables 2 and 4) of the total emergy yield, while local non-renewable resources only contributed 8.68% (Table 2). This suggests an environmentally sustainable system performance. Compared to other food production systems, except for the indigenous Mayan system, the commercial way of producing cattle in Argentina, according to our analysis of the cattle system, is to a high extent based on local renewable emergy sources and generates products with a high sustainability index as shown in Table 4.

Studying a system from an emergy perspective involves more than just considering the physical flow of items in the system in order to obtain a product. Emergy analysis gives a more comprehensive picture of the environmental contributions to a product or service compared to other accounting methods, both biophysical and economic, since it recognizes the participation done by nature, direct and indirect via society. The work done by nature is usually taken for granted and therefore not considered. In the grazing cattle system, emergy evaluation showed that rain contributed 61% of the total emergy, and it was the main local renewable resource contribution. Any development or strategy for designing or providing incentives for this system should be planned

Table 4
Comparative emergy indices from different food productions

	Renew[a]	EYR[a]	ELR[a]	ESI[a]	EIR[a]	Source
Grazing cattle Argentina	0.65	3.73	0.55	6.80	0.37	This study
Rainfeed intensive agriculture 1996	0.31	2.99	2.27	1.32	0.50	Ferreyra (2001)
Organic soy been production Brazil	0.42	1.78	1.40	1.27	1.27	Ortega et al. (2003)
Chemical soy been (fertilizers + pesticides)	0.23	1.74	3.40	0.50	1.35	Ortega et al. (2003)
Convencional pig in Sweden	0.26	1.04	[b]22.32	0.05	[b]22.32	Andresen et al. (2000)
Ecological pig in Sweden	0.57	1.13	[b]7.79	0.15	[b]7.79	Andresen et al. (2000)
Corn production USA	0.05	1.07	18.83	0.06	13.87	Martin et al. (2006)
Indigenous production Mexico	0.91	12.17	0.10	115.98	0.09	Martin et al. (2006)

[a] Renew (%renewability/100); EYR (emergy yield ratio); ELR (environmental loading ratio); ESI (emergy sustainability index); EIR (emergy investment ratio).
[b] Not available data about local non-renewable resources.

taking into account rain as an important flow driving production. The study also showed that the system is nested in the larger national context evaluated by Ferreyra (2001), from which it also receives feedback. With an emergy analysis approach, maximizing economic (human) production and sustainability includes the flows of energy and matter that cycle in the geobiosphere in both converging and diverging pathways. Any system is dependent on its resource base as well as from feedback flows from larger scales.

4.1. Systems behavior through self-organizing patterns

Self-organizational processes take place on all scales at the same time and include the intermediate loading, speed and efficiency that maximize power (Odum and Odum, 2001). By doing an emergy analysis it was possible to study parts (subsystems) without losing the vision of a whole system. It was also possible to identify and explore the coupled systems that were embedded in the whole system and contributed to the same final product. There were two main coupled subsystems: natural pasture coupled with cow–calf operation, and sowed pasture-*verdeo* coupled with wintering-fattening. These were also coupled, and a third subsystem of horse-pasture acted indirectly to make possible the output. These patterns are summarized in Fig. 6.

The lower ESI calculated for the complete system (6.80) in comparison with the cow–calf operation (14.20) and wintering-fattening (7.96) studied separately, could be a function of analyzing the system as a whole instead of only by subsystems. This captures the interactions among all of the subsystems and emergent system properties that influence final outputs. Even though the complete cycle

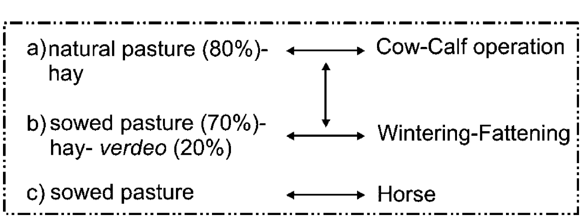

Fig. 6. Coupled subsystem of grazing beef cattle system.

performs well in its natural-economic context, analyzing the different subsystems that are nested in the system made it possible to identify the ones that need special mention or where changes or incentives should be focused.

Cow–calf operation relies mostly on natural pasture, and both subsystems (natural pasture and cow–calf) perform well in the present and in the long range since they have the highest ESI (Table 3). These coupled units have relatively moderate local non-renewable (soil organic matter) emergy requirements (13.5–16.7%), which implies the need for monitoring their performance. On the other hand, transformity of natural pasture is higher than sowed pasture, due to its higher complexity and less yield than the pasture sowed and treated with chemicals. Natural pasture subsystem also showed the lowest EIR among the subsystems. A relatively low value suggests that this subsystem could respond well to investments, such as more time for a better recovery of grass and soil, or using inter-sowing patterns. This could reinforce feedback without increasing external inputs significantly and improve production. Complemented with studies of nutrient recycling, this is an example of how results of an emergy analysis could be used to identify subsystem potentials for improvement.

There is a deterioration and decrease of natural pasture productivity due to seasonal production without controlling the stocking rate as reported by Deregibus (1988). We speculate that the loss of some pasture species and the emergence of new ones represent the self-organization behavior of the system in order to maximize empower. To keep subsystems performing well in the long term it is important to consider ways of promoting feedback through suitable management.

The other coupled system is steers for slaughtering that mostly graze on sowed pasture (70% of their feed requirements). Results indicate that it could be a vulnerable production system in the future since the system tries to maximize its empower according to current human intervention through management. The increase of grazing cattle production due to new markets and incentives could accelerate the present trend of relying more on external purchased inputs for sowed pasture which will increase its already relatively high EIR (0.84–0.90). These are high compared with values reported by Ferreyra (2001) for rainfed intensive agriculture (EIR = 0.5) shown in Table 4 as well as for the whole country of Argentina (EIR = 0.15) (Ferreyra, 2001), with an overall result of increased production with less efficiency.

Hay coming from natural pasture and hay from sowed pasture have the highest transformities among primary production activities. There is a small amount of material used in relation to the environmental and society emergy requirements needed. Making hay is a way to manage spring overproduction. However, it seems more suitable to make hay with a bigger percentage of the grass production area.

4.2. Insights for the current and future situation

The EIR of the complete cycle of grazing cattle (0.37) was higher than the ratio prevailing in the country (0.15) calculated and reported by Ferreyra (2001), but lower than that of modern agriculture (0.5) (Table 4). In the overall situation and with the present data, grazing cattle production could be less attractive to new investments by people outside the agricultural sector, but feasible for farmers to increase land uses for livestock production. Government and farmers are willing to increase livestock production due to favorable external markets, but world prices have made agricultural crops highly attractive for short-term economic returns.

According to this research, an increase of livestock production could lead to the increase of external purchased inputs applied to sowed pasture. This strategy could be risky since the environmental load and investment ratio will increase and the result could be inefficient production in the long term. One approach is to develop regulations that encourage farmers to rely more on natural resources. National or regional regulations and integrated plans are needed to ensure environmentally sustainable productivity of this activity and long-term farmer financial well being. Appropriate regulations should not only promote the use of renewable resources but also assure adequate feedback from the larger system. Inappropriate extraction of natural resources eventually eliminates natural capital (Odum and Odum, 2001). This is challenging, since regulations are needed to ensure the long-range productivity and welfare of the region, yet they are conditioned by complex interactions of factors at the national and international levels beyond control of farmers.

5. Conclusions

Conventional cattle grazing in Argentina provides a desirable product for internal and external markets. Government, research institutions and farmers have focused attention more on markets than on environmental sustainability of cattle production for obvious short-term economic reasons. Emergy analysis of grazing cattle for meat production, a method that evaluates inputs coming from nature and those coming from society, shows that all driving forces to the system need to be considered in evaluating production methods and management strategies. The long-term goal is sustainable resource use as well as profitability. Careful attention should be given to efficient use of rain, which contributes 61% of the total emergy. Grazing can be an environmentally sustainable activity without much loading of the environment. Specific subsystems such as sowed pasture and natural pasture need special attention in order to avoid decisions that reduce their positive contributions to the economy and the environment.

Sowed pasture has a relatively high dependency on external inputs and moderate use of local non-renewable resources. This subsystem could become vulnerable in the future, with negative impacts on the environment, if there are not adequate environmental regulations and support for proper production methods. Natural pastures have the highest environmental sustainability and the lowest load on the environment. Enhanced management and appropriate investment alternatives must lead to preserving soil and grass resources.

Both natural and sowed pastures need special attention since they are the basic subsystems where grazing cattle are raised and are essential for producing meat for export and internal consumption. Exploring the emergy investment, we found that grazing cattle provide an efficient option compared with modern crop production and this system helps protect the environment. Yet grazing cattle currently are less profitable according to short-term economic analysis. It is essential to enlist farmers in the care of local resources since these are the basis for regional or national welfare. Recommended grazing management alternatives that both protect and rely on natural resources are available from research departments and institutions. It is also important to develop the effective application of environmental regulations that address not only soil, water, and biodiversity, but also promote more reliance on renewable resources in order to ensure the current and future success of grazing systems.

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