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Emergy evaluation of contrasting dairy systems at multiple levels

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A B S T R A C T

Emergy accounting (EmA) was applied to a range of dairy systems, from low-input smallholder systems in South Mali (SM), to intermediate-input systems in two regions of France, Poitou-Charentes (PC) and Bretagne (BR), to high-input systems on Reunion Island (RI). These systems were studied at three different levels: whole-farm (dairy system and cropping system), dairy-system (dairy herd and forage land), and herd (animals only). Dairy farms in SM used the lowest total emergy at all levels and was the highest user of renewable resources. Despite the low quality of resources consumed (crop residues and natural pasture), efficiency of their use was similar to that of industrialised inputs by intensive systems in RI, PC and BR. In addition, among the systems studied, SM dairy farms lay closest to environmental sustainability, contradicting the usual image of high environmental impact of cattle production in developing countries. EmA also revealed characteristics of the three intensive systems. Systems from RI and PC had lower resource transformation efficiency and higher environmental impacts than those from BR, due mainly to feeding strategies that differed due to differing socio-climatic constraints. Application of EmA at multiple levels revealed the importance of a multi-level analysis. While the whole-farm level assesses the overall contribution of the system to its environment, the dairy-system level is suitable for comparison of multi-product systems. In contrast, the herd level focuses on herd management and bypasses debates about definition of system boundaries by excluding land management. Combining all levels highlights the contribution of livestock to the global agricultural system and identifies inefficiencies and influences of system components on the environment.

1. Introduction

Climate change and pollution have led to global concern about environmental impacts of human activities. Livestock farming is primary among these societal challenges. It is currently held responsible for 18% of greenhouse gas emissions of the planet (Steinfeld et al., 2006). Since the global human population will potentially increase to 9.2 billion by 2050 (United Nations, 2007), and with increasing numbers of people in middle classes in developing countries, global demand for animal products will increase (FAO, 2009). In this sense, assessing livestock systems and increasing their production without increasing their environmental impact is a major challenge.

Many methods have been used to assess environmental impacts of livestock systems. Most concern life cycle analysis (de Vries and de Boer, 2010) or ecological footprint (Berg et al., 1996; Kautsky et al., 1997; Kissinger and Rees, 2009; van der Werf et al., 2007). The concept of emergy accounting (EmA) has existed for several years (Castellini et al., 2006; Cavalett et al., 2006; Li et al., 2011; Rótolo et al., 2007; Xi and Qin, 2009; Zhang et al., 2011); however, if EmA has been yet applied to animal production, few studies concern dairy systems (Bastianoni and Marchettini, 2000; Agostinho et al., 2008). Emergy is defined as the available energy of a certain kind that has been used, directly or indirectly, to make a product or provide a service (Odum, 1996). It is usually quantified in solar-energy equivalents and expressed as solar emJoules (seJ). This allows for accounting on a common basis all the inputs that contributed to the construction of a product, including environmental ones that are considered "free" in energy or life cycle analyses. EmA is used to measure environmental stress, especially when estimating long-term sustainability in natural-resource management (Ulgiati and Brown, 1998).

Increasing demand for animal products particularly concerns milk, whose production is expected to double between 2000 and

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2050 (Steinfeld et al., 2006). Milk production occurs throughout the world in a variety of forms, from extensive smallholder systems with low inputs to confinement systems with high inputs. In most cases, milk production represents the central economic activity of farms with a dairy subsystem (FAO, 2009). Assessing and comparing contrasting dairy-production systems is an important goal. Thus, the main aim of this study was to perform EmA on such a range of dairy-production systems: low-input smallholder systems in South Mali, intermediate-input systems in two regions of France (Poitou-Charentes and Bretagne), and a high-input system on Reunion Island. Moreover, few livestock systems have been assessed with EmA (Vigne et al., 2012), in particular dairy systems (Bastianoni and Marchettini, 2000; Brandt-Williams, 2002). This paper offers an emergy assessment of contrasting dairy systems, aims to cover a lack of information about EmA of dairy systems, and discusses the utility of assessing multiple farming-system levels.

2. Materials and methods

2.1. Description of the territories and dairy-production systems

South Mali (SM) corresponds to the peri-urban region of Sikasso (11° 19′ N, 5° 40′ W) and is representative of western African savannah. The local climate has a relatively high mean temperature (26 °C) and two seasons: a dry season from December–May and a rainy season from June–November, during which precipitation averages 1.1 m. The area contains approximately 70% natural pasture and 30% cash & food crops (Table 1). To cultivate cash & food crops, human labour is supplemented by draft animals. Fertilisation is based for a large part (66%) on manure, mainly due to the high cost of mineral fertilisers. Cattle herds are usually small and composed of local breeds of cows and zebus with a wide diversity of ages and types (e.g., calves, dairy cows, draft cows, bulls) fed by crop residues and grazing on natural pasture. Few feed concentrates are distributed, illustrating the low intensification of herds, which results in low milk yield (212 l cow^{-1} yr^{-1}). SM systems can be considered low-input systems.

Reunion Island (RI) is a French territory in the Indian Ocean (21° 09′ S, 55° 30′ E) with a tropical climate. It has relatively high mean temperature (24 °C) and annual precipitation (3.1 m) but localised mesoclimates. For example, the eastern part of the island is exposed to trade winds and is humid (3.0–6.0 m of precipitation per year), whereas the western part, protected by the central mountains, receives less than 1.0 m of precipitation per year. This diversity of terrain and climate has led to different feeding strategies. Below 800 m of altitude, the forage crops cultivated are tropical, whereas above this limit, tropical and temperate species are associated (Barbet-Massin et al., 2004). Herds mainly consist of the Holstein-Friesian breed and have a mean size of 55.5 livestock units (LU). Produced forages are mainly ensiled and distributed to animals (Table 1). Lack of arable land has led to a high stocking rate (4.4 LU ha^{-1}) and high supplementation of feed concentrates (4672 kg LU^{-1} yr^{-1}). The mean mineral fertilisation rate is high (194 kg N ha^{-1} yr^{-1}) to optimise biomass production. High quantities of concentrates and mineral fertilisers make RI systems high-input systems.

Poitou-Charentes (PC) is a region in western France (46° 05′ N, 00° 10′ E) with an oceanic climate characterised by precipitation distributed throughout the year (0.9 m) and a moderate mean temperature (13 °C). It has relatively large farms with relatively large herds (94.4 LU), mainly Holstein-Friesian and Normande breeds (Table 1). Farms are diversified, ranging from specialised dairy systems to mixed crop-livestock systems. The mean percentage of grazing area in total farm area is relatively high (48%), but a low mean stocking rate leads to low availability of manure and thus a relatively high mean quantity of mineral fertiliser applied (77 kg N ha^{-1} yr^{-1}). Grassland biomass production is relatively low, but mean distribution of feed concentrates exceeds 2000 kg LU^{-1} yr^{-1}, which leads to high milk production (7515 l cow^{-1} yr^{-1}).

Bretagne (BR) (48° 20′ N, 02° 70′ W) is also located in western France and has a climate similar to that of PC. Dairy farms are smaller, however, with fewer animals (Table 1). Crops are less common because dairy systems are more specialised. Mineral fertilisation on forage land is lower than that in PC (41 kg N ha^{-1} yr^{-1}), while grassland biomass production is higher. Milk production is relatively high (7012 l cow^{-1} yr^{-1}), but distribution of feed concentrates is low (1311 kg LU^{-1} yr^{-1}). Consequently, in this study, both PC and BR systems can be considered intermediate-input systems.

2.2. Application of emergy accounting

Detailed description of emergy methodology is given by Odum (1996) and others (Brown and Ulgiati, 2004; Ulgiati and Brown,

Table 1
Mean (and minimum–maximum) characteristics of studied farms in the four territories (SM: South Mali, RI: Reunion Island, PC: Poitou-Charentes, BR: Bretagne).

Territory (number of farms studied)	SM (n = 14)	RI (n = 30)	PC (n = 48)	BR (n = 38)
Herd size (LU)	32.8 (9.8–64.8)	55.5 (24.0–131.2)	94.4 (27.9–220.0)	79.2 (38.0–125.5)
Dairy cows in herd (%)	52 (37–100)	78 (57–100)	66 (56–98)	66 (51–82)
Usable agricultural area (UAA) (ha)	36.5 (6.1–76.7)	22.0 (2.5–72.0)	135.3 (30.0–378.3)	80.3 (28.6–200.0)
Forage-crop area in UAAC (%)	70 (10–100)	100 (100–100)	60 (15–100)	78 (56–100)
Non-forage crop area in UAA (%)	30 (0–90)	0 (0–0)	40 (0–85)	22 (0–44)
Overall farm stocking rate (LU.ha^{-1})	1.0 (0.5–1.6)	4.4 (1.2–10.8)	0.8 (0.3–1.4)	1.1 (0.6–1.7)
Forage-crop area stocking rate (LU.ha^{-1})	2.4 (0.7–16.8)	4.4 (1.2–10.8)	1.5 (0.4–3.8)	1.4 (0.6–2.2)
Human workforce (AWU)	4.3 (2.6–9.8)	2.5 (1.3–4.5)	2.5 (1.0–4.5)	1.8 (1.0–3.5)
Grazing area in UAA (%)	0 (0–0)	27 (0–58)	48 (26–100)	70 (50–90)
Mineral N on cash & food crops (kg N ha^{-1})	33 (6–57)	–	95 (0–197)	94 (0–161)
Organic N on cash & food crops (kg N ha^{-1})	64 (11–187)	–	22 (0–147)	23 (0–148)
Mineral N on forage crops (kg N ha^{-1})	–	194 (30–1022)	77 (0–220)	41 (0–93)
Organic N on forage crops (kg N ha^{-1})	–	91 (0-383)	52 (0–260)	86 (16–344)
Concentrate feeds (kg LU^{-1})	123 (0–365)	4672 (2375–7375)	2020 (338–3649)	1311 (663–2082)
Grassland production (t DM ha^{-1})	1.9[b]	12.6 (6.2–24.4)	5.8 (3.9–9.0)	6.4 (5.5–7.5)
Silage production[a] (t DM ha^{-1})	–	22.6 (10.2–45.2)	12.8 (10.0–17.0)	13.4 (7.1–17.0)
Cereal yield (t ha^{-1})	1.6 (0.3–4.5)	–	6.0 (4.0–6.5)	8.0 (5.5–11.5)
Milk yield (l cow^{-1})	212 (56–1130)	6082 (3545–9314)	7515 (4627–9719)	7012 (4757–8950)

LU: Livestock Unit (1 LU = 250 kg of animal body weight for SM and 500 kg for RI, PC and BR), AWU: Agricultural Workforce Unit, corresponding to the number of persons usually working on farms, DM: dry matter.
[a] Grass silage in RI and maize silage in PC and BR.
[b] Estimated from Penning de Vries and Djitèye (1982).