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Resource use assessment of an agricultural system from a life cycle perspective – a dairy farm as case study

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ABSTRACT

Despite the great pressure on global natural resources, few LCA studies focus on total resource consumption and the efficiency of the use of those resources. Moreover, a total resource use assessment for agricultural systems is highly relevant because many of these systems have become high input/high output systems in order to achieve higher productivity. In this study, we propose a framework to evaluate total resource consumption of agricultural systems at the process level using an Exergy Analysis (EA) and at the life cycle level using an Exergetic Life Cycle Assessment (ELCA). We evaluate the applicability and usefulness of this approach based on a case study of an intensive confinement-based dairy farm in the region of Flanders, Belgium. The EA showed that more than half of the resources consumed by the dairy farm's herd was irreversibly lost, as a consequence of the second law of thermodynamics. The remaining went for almost two-thirds to manure (54%) and methane emissions (9%), while only one-third flowed to end-products, i.e. milk (32%) and the animals awaiting slaughter (2%). The ELCA identified the feed supply as the most demanding part of the dairy production chain by far, representing 93% of the resource footprint. Overall, concentrates were on average 2.5 times more resource-intensive per kg dry matter than roughages, while wet by-products were 34% and 73% less resource-intensive than roughages and concentrates, respectively. Mainly land (77%) and fossil resources (17%) were required throughout the life cycle. About 36% of the occupied land (in terms of m^{2*}year) was located off-farm. Slightly less than one-quarter of the fossil resources were used on-farm as fuel and electricity. The on-farm use of groundwater accounted for about half of the total *blue* water use across the life cycle. With this paper, we show the usefulness of the proposed framework to evaluate total resource consumption of dairy farms and to identify on-farm and off-farm improvement opportunities. This framework has potential to support research on whole-farm improvement strategies such as pasture-based systems and low-input farming, and to compare populations of contrasting milk production systems.

1. Introduction

The global stocks of natural resources, all of which support our human activities, are under pressure. Natural resources include water, minerals, metals, land, fossil resources, etc. We are consuming natural resources at an unsustainable rate that exceeds the carrying capacity of the Earth (Global Footprint Network, 2012). Since the 1980s, the global annual extraction of resources has increased by almost 50% (from 40 billion tonnes to 58 billion tonnes) and it is expected to rise further to 100 billion tonnes by 2030 (SERI, GLOBAL 2000 and Friends of the Earth Europe, 2009). Due to the increasing standard of living in developing countries, the global resource extraction is even expected to rise about 25% faster than the growth of the worldwide population, which is projected to increase from around 6 billion today to 8.3 billion in 2030 (FAO, 2002). The European Commission's publication entitled *A resource-efficient Europe – Flagship initiative under the Europe 2020 strategy* (European Commission, 2011) also supports the notion that the sustainable development of our society should rely on increased efficiency of resource use. Striving for higher resource use efficiency is especially relevant for Europe, because it is the continent with the largest net-import of natural resources (SERI, GLOBAL 2000 and Friends of the Earth Europe, 2009).

Agriculture should also face the challenge of increasing its resource use efficiency. The Food and Agriculture Organization (FAO, 2011), in its book *Save and Grow*, states that 'to feed a growing world population, we have no option but to intensify crop production. But farmers face unprecedented constraints. In order to grow,

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agriculture must learn to save.' During past decades, the increase in agricultural productivity, the so-called *Green Revolution*, has mainly been achieved by an increased material and energy input (fertilisers, pesticides, irrigation, machinery powered by fossil fuels, etc.) and has been accompanied by environmental burdens (greenhouse gas emissions, eutrophication, acidification, etc.). Along with the rising environmental concerns, especially about livestock farming (FAO, 2006, 2013), livestock systems have increasingly been studied using Life Cycle Assessment (LCA). LCA is a commonly accepted method to evaluate the environmental sustainability of a product throughout its entire life cycle (Guinée et al., 2002). Animal-derived food products, especially red meat and dairy products, tend to have higher environmental impacts than plant-based foods (Heller et al., 2013; Meier and Christen, 2013; Vanham et al., 2013). Many LCA studies have been performed on livestock products such as beef, chicken, eggs, milk and pork (de Vries and De Boer, 2010). Frequently studied environmental aspects can be classified into two types of impact categories: 1) emissions, e.g. global warming, eutrophication and acidification, and 2) resource use, e.g. land use and primary energy use. Primary energy use includes both non-renewable energy resources, such as fossil and nuclear energy, and renewable energy resources, such as solar energy, wind energy, hydropower, etc. Although in the past emission-related impacts were more frequently evaluated in LCA studies than resource use aspects, many recent LCA studies on livestock products have quantified both primary energy use (MJ) and land use (m^2) (e.g. da Silva et al., 2014; O'Brien et al., 2012). Also recently, water consumption has gained more attention, especially in studies on milk production (e.g. de Boer et al., 2013; Sultana et al., 2014). Some of the studies that investigated energy use also focused on the efficiency with which these energy resources were used (Meul et al., 2007; Vigne et al., 2013). However, a more extended resource assessment can be achieved when land occupation and non-energetic resources, i.e. water, metals and minerals, are addressed in addition to energy carrying resources (Dewulf et al., 2007a). An assessment of the full range of resources is needed to avoid environmental problem-shifting in resource consumption. The study of De Meester et al. (2011) is a good illustration of how important it is to analyse "total" resource use. Their study revealed that the production of fuel bioethanol in a biorefinery to replace petrol can save 27% of fossil resources, but this comes at the cost of 93% extra land, water and minerals. An integrated assessment of total resource consumption and its efficiency is observed as a gap in existing LCA research of livestock systems.

Such an integrated assessment of resource consumption considers energy resources and non-energetic resources at the same time. In order to calculate overall resource efficiencies, one needs a single quantifier for both material and energy flows. The exergy concept, which originates from the second law of thermodynamics, is stated to be an appropriate quantifier for both the amount and quality of material and energy flows in one common unit, i.e. joules of exergy. According to the second law, every process transforms resources into work, heat, and/or products, by-products and wastes, and generates entropy. The sum of the exergy embodied in these outputs is lower than the input of exergy in the resources, because part of the initial exergy is dissipated through irreversible entropy production. The quality of resources thus decreases in every transformation step. The calculation of the total exergy of a flow is usually split up into several components (physical, chemical, kinetic, potential, electric, etc.) (Dewulf et al., 2008; Szargut et al., 1988; Wall, 1977). In this paper, we introduce a generic framework that uses the exergy concept to evaluate the resource efficiency of agricultural systems. To build this framework, we have chosen specialised dairy farms in Flanders (the northern region of Belgium) as a starting base; then we have drawn a generic process flow diagram for these farms. The main reason for choosing dairy farms is that these farms include both plant and animal production, which interact by feed production and manure utilisation. The process flow diagram can therefore be used as a blueprint for other agricultural systems with only minor modifications or deletions (e.g. on-farm feed production is usually not present at pig farms). In the light of the trend towards more intensively managed and more specialised dairy farms during the past decades in Europe (CEAS Consultants, 2000), and more specifically in Flanders (Van der Straeten et al., 2012), we chose to evaluate this framework with a case study of one specific intensive confinement-based dairy farm in Flanders.

The generic framework is characterised by a thorough input/output analysis of the dairy farming system, meaning that the system was not considered as a *black box*. Dairy farms are rather complex systems that are composed of several subsystems with interactions among them. For that reason, we considered internal flows of dairy farming systems in order to thoroughly understand those systems. The resource efficiencies of the dairy farming system and of the identified subsystems were calculated after quantifying all flows in exergy terms. This approach, called an Exergy Analysis (EA) (Szargut et al., 1988), indicates how efficiently resources are converted into products. An EA also allows the identification of improvement opportunities from a resource point of view. However, the boundaries of such an EA can be enlarged to include the supply chains of the dairy farm. Application of the exergy concept to LCA results in Exergetic Life Cycle Assessment (ELCA) (De Meester et al., 2009). In this paper, a total resource consumption footprint was quantified using the exergetic life cycle impact assessment method, named *Cumulative Exergy Extraction from the Natural Environment* (CEENE), developed by Dewulf et al. (2007a). This method makes it possible to assess energy carriers, non-energetic resources and land occupation, all quantified in terms of exergy.

2. Materials and methods

2.1. Scope definition

We have performed a case study of a confinement-based specialised dairy farm in Flanders according to the ISO 14040/14044 guidelines (ISO, 2006a, 2006b). The boundary of the study involved the life cycle from cradle to farm gate; the functional unit was defined as 1 kg fat-and-protein-corrected milk (FPCM) (4% fat and 3.3% protein content (IDF, 2010)). The foreground system was defined as the entire dairy farm, i.e. the production unit within the gate-to-gate boundary (Fig. 1), including on-farm feed (roughage) production and manure utilisation. The background system was defined as the part of the production chain outside the dairy farm boundary, including all human–industrial processes (agricultural, industrial and transport) necessary to produce and deliver the inputs to the dairy farm. Regarding the handling of co-products, more information can be found in section 2.4., "Allocation procedure".

2.2. The foreground system

2.2.1. Description of the foreground system

Starting with a detailed analysis of specialised dairy farms in Flanders, we drew a generic process flow diagram (Fig. 1). Based on the nomenclature for system boundaries used by Dewulf et al. (2007b), the foreground system (β) was divided into a core subsystem (α) and subsystems (β_i) that support the core activity. In doing so, the foreground system was divided into five subsystems: the α-core subsystem *dairy production* and the β_i-supporting subsystems *roughage production* (β_1), *water supply and pretreatment* (β_2), *renewable energy/hot water/heat production* (solar panels, solar boilers and anaerobic digesters) (β_3) and *wastewater treatment* (β_4). The α-core subsystem