A framework for assessing the energy efficiency of non-mechanised agricultural systems in developing countries

Francis Molua Mwambo[1], Christine Fürst[2]

Abstract

There is a continuously growing global demand for agricultural products, including food, fodder and fuels that urges for reasons of ensuring a sustainable development innovative methods to assess the impact of agricultural management. Existing methods of energy efficiency analysis for agricultural systems take into account human labour and draft animal power as inputs and consider also land-use characteristics as factors affecting the production in systems in most developing African countries. However, most of these methods fail to address properly different scales in decision making, i.e. connecting the management planning level with regional development considerations. With this paper, we introduce an alternative method to assess the energy efficiency in agronomic land-use. Our work intends to conceive a comprehensive and scale sensitive assessment framework that supports consulting land-use, decision making, and policy planning.

1. Introduction

Agricultural intensification involving the cultivation of high-yielding crop varieties combined with the application of sufficient fertilizers, pesticides and irrigation have been proposed as a relevant solution to address the problem of food insecurity menacing the majority of the population in many developing countries. But such strategy will likely be constrained by the rapidly increasing energy demand. According to [6] the global agricultural productivity is expected to be increased by as much as 50-70% by 2030 in order to meet the increasing human demands for food and other biomass-based products. The increases expected from developing countries' are at the upper margin considering the fact that their current productivity is lower and at the same time most of the population growth is occurring in developing countries compared to the developed countries. Figure 1 shows an agricultural performance review of Africa and 2 other developing regions over the last 50 years. The trend reveals that Africa is grossly lagging behind in productivity compared to the other developing regions [10]. Africa's productivity is hampered mostly by constraints of energy and land-use among other factors. Tackling the problem from a sustainable development standpoint has provoked the need for an alternative method that can be used to better analyse the energy efficiency considering African land-use schemes including inputs from human and draft animal labour. An accurate analysis will reveal decisive information through which the energy efficiency in agriculture can be improved, including the necessary support for the formulation of such energy efficiency oriented policy.

Furthermore, we are faced with a continuously growing global demand for energy that is intended to be fed more and more by renewables and here especially by biofuels [11]. Consequently, for agriculture being a consumer and producer of energy at the same time [9], energy efficiency analysis supports optimising the sustainable use of energy [11, 13, 18, 1, 2].

[1] Center for Development Research (ZEF), University of Bonn, Walter-Flex Str. 3, 53113 Bonn, Germany, fmwambo@uni-bonn.de, Department of Ecology and Natural Resources Management

[2] Center for Development Research (ZEF), University of Bonn, Walter-Flex Str. 3, 53113 Bonn, Germany, cfuerst@uni-bonn.de, Department of Ecology and Natural Resources Management

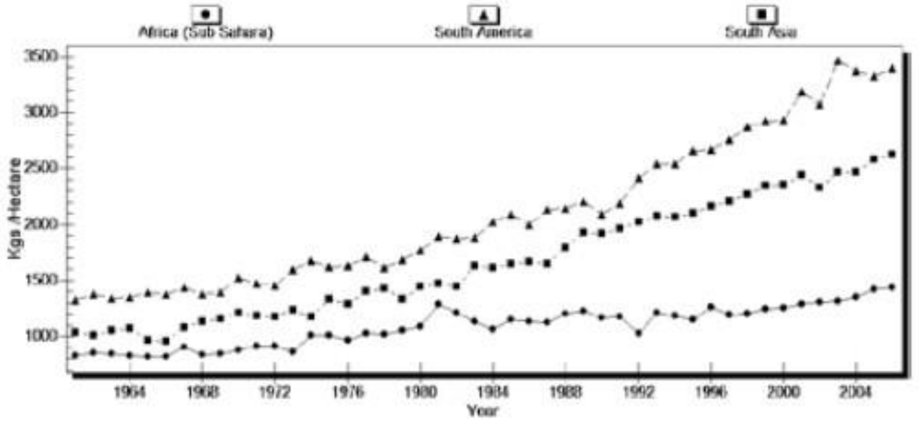

Figure 1: Cereal Yields per Hectare: Africa versus Latin America versus South Asia (Copied from Kariuki, (2011) who states the original source)

Energy efficiency analysis describes the role of direct and indirect energy inputs in the production system. Until now, relatively few studies on energy efficiency analysis have been conducted on agricultural systems in developing countries [26]. So far, there is no standardized and sufficiently reliable method for analysing energy efficiency in non-mechanised agricultural systems as is the case in most African developing countries where human labour and draft animal power are still predominant input energy sources as shown in Table 1.

Region		**Percentage of area cultivated by different power sources**		
		Human Labour	**Draught Animal**	**Tractor**
All developing countries	1997/99	35	30	35
	2030	25	20	55
Sub-Saharan Africa	1997/99	65	25	10
	2030	45	30	25
North East/North Africa	1997/99	20	20	60
	2030	10	15	75
Latin America and the Caribbean	1997/99	25	25	50
	2030	15	15	70
South Asia	1997/99	30	35	35
	2030	15	15	70
East Asia	1997/99	40	40	20
	2030	25	25	50

Table 1: Proportion of area cultivated by different power sources (Source: [6 p.153])

Already in 1995, the FAO [5] states (see also Figure 2): "Human and animal labour requirements fall outside the traditional boundaries of energy sector planning, and their dynamics are far more complex than those of fuel and electricity supply. However, since human labour remains the predominant source of energy for agricultural production in much of Africa, and transitions to animal traction and fuel using machinery are important for the social and economic effects, human and animal labour requirements and trade-offs remains an important area for research." Consequently, adapted approaches that respect the specifics of subsistence agriculture need to be developed.

As a preliminary approach, this paper presents the conceptualisation of a comprehensive framework for assessing energy efficiency in subsistence agricultural production systems. In the subsequent section 2 we examine shortcomings of current methods of energy efficiency in analysing non-mechanised agricultural systems in developing countries. This is followed by section 3 on how to conceive the methodological framework. Finally, in section 4 we summarise how we envisage the further development and application of the framework.

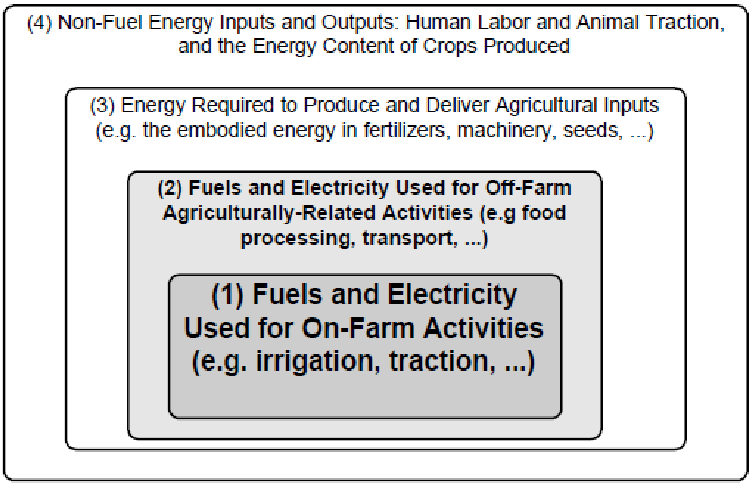

Figure 2: Levels of agricultural energy analysis by FAO (Source: [5])

2. Requests for improving energy efficiency analysis

There has always been a need for alternative approaches through which energy analysis could lead to sustainable development in developing countries' agriculture. In 1993, the United Nations [25 Chapter 14] emphasises on the relationship between energy and agriculture. It underscores the need to enhance productivity and thus, sustainable development in developing countries. In 1995, the FAO [5] reiterates that agricultural productivity is closely associated to direct and indirect energy inputs; and policies are required to consolidate this relationship to the benefit of farmers. However, agricultural development policies in most African countries are designed and implemented with little or no regard to this association. Consequently, opportunities which can enhance production in both quantitative and qualitative terms are often lost. Energy development plans in most developing African countries rarely take into consideration the present and future energy needs of agriculture.

Energy efficiency is a widely used term with different meanings in public policy making. Efficiency is the ability to produce an output from the minimum resource level required [22] while the ratio of energy output to energy input defines the energy efficiency [19]. According to [17] a distinction between energy conservation and energy efficiency is that the former is a change in behaviour while the latter involves an adoption of a particular technology that enhances energy saving. The advent of the concept of energy analysis was initiated in order to account for the fact that when heat or work is put into or taken out of a system and that system ends up in a different state. Consequently, some property of the system has to account for the difference. Thus, a given system under a given set of conditions has certain energy content as explained in [24]. Following the distinction made in [17 p.4787] a combination of both energy conservation and energy efficiency may be necessary in some developing countries. For instance, it may require farmers in developing countries to primarily change their behaviour from traditional land-use practices before adopting alternative land-uses that might have been recommended in a policy aimed at improving energy efficiency in agriculture.

The shortcomings of existing methods of energy efficiency analysis stem from the fact that the energy inputs from human, and draft animal labour in developing countries are often ignored [23 p.129] even though these inputs may be enormous [21 p.129] . [27, 28] consider energy inputs from various sources including humans and draft animals in agricultural systems in developing countries. However, most analyses were targeted at farm scale [28, 27]. Scenarios that involve also different management strategy below farm scale have so far rarely been considered in energy efficiency analysis [28]. The links between agricultural energy inputs, yields, economic returns, land requirements and land-use change need further research [11, 29]. The information contained in existing methods could much more be useful if land-use and land management are integrated in a standardized energy analysis methodology. An overall advantage of integrating land-use and land management would be that energy efficient management and land-use strategies can be recommended as benchmark when formulating agricultural policies. Also, most of the currently applied methods ignore the regional interplay of energy fluxes which is so decisive for sustainable rural development in developing countries. Finally, existing methods of farm energy efficiency use different approaches and subsequently produce different results [15 p.356]. Furthermore, there are difficulties in comparing different agricultural systems using existing methods because of the non-uniformity in the units in which energy efficiency is measured [23 p.123].

3. Methodological framework

To further develop the concept of energy efficiency analysis, we suggest combining the eMergy approach by Odum [16] and a technique in Data Envelopment Analysis (DEA) pioneered by Farrell [7] and later improved by Charnes *et al*., [3]. EMergy is a concept to better allocate and account for energy influxes (both inputs and outputs) in a production system. Its broader perspective of environmental inputs, direct connection to economics, and internal optimising principle [8] are a plus in analysis especially as energy, economics, and the environment are considered mutually dependent [26, 14]. Using transformity coefficients the influxes are converted to their energy equivalents measured in Solar eMergy Joule (SeJ) and subsequently analysed using DEA to process information in a way that enhances decisions making and energy efficiency oriented policies in agriculture. DEA is a non-parametric linear programming methodology through which it becomes possible to compare the productivity of different agricultural land use practices by considering a system of inputs and outputs. The best practice is benchmarked and the relative energy efficiency that can be improved in the other land uses that are not benchmarked can be calculated. Another advantage is that different land use schemes are considered in the DEA analysis. The application of DEA is also useful to obtain result that is informative as much as possible even when there are constraints in the data [2].

For this study, data on agricultural land use, crop yield, human and draft animal labour in agriculture are sought from the BiomassWeb Project partner institutions including the affiliated agricultural services in Ghana. Since developing countries' subsistence agriculture is rainfed, meteorological data on the rainfall and other renewable energy inputs from nature can be informative. Table 2 shows exemplarily the energy influxes in a non-mechanised agricultural system while Table 3 shows the agronomic land use characteristics commonly practiced in non-mechanised agricultural systems in Ghana as a representative developing country in West African. Figure 3 shows our suggested overall framework for an enhanced energy efficiency analysis that could cope with the specific problems of animal and human labour in African agricultural systems.

Renewable energy inputs from nature	Non-renewable energy inputs from nature	Purchased energy Inputs	Service energy inputs	Biomass energy outputs
Solar energy for photosynthesis Wind (kinetic energy) for pollination Rain for rain-fed irrigation Earth for geothermal/ geochemical input	Topsoil loss associated with agricultural land use & farming practices Seeds/ seedlings for sowing	Fertilizers Pesticides Other chemicals	Human labour Draft animal labour	e.g. crop yield

Table 2: A list of exemplary energy inputs and outputs in a non-mechanised agricultural system

Farming system	Farming practice	Effect of soil
Rotational bush burning	Slash & burn. Fallow period with or without fertilizer	Destruction of vegetative cover, Expose soil to erosion, Leaching of soil nutrients.
Permanent tree crop system	Slash & burn but presence of tree canopy	Minimal soil loss by erosion due to tree canopy.
Compound farming system	Slash & burn with or without fertilizer/ manure. Livestock grazing	Soil loss due to erosion, leaching of nutrients, Soil compaction due to livestock.
Mixed farming system	Slash & burn with or without fertilizer/ manure	Soil erosion & nutrient depletion.
Special horticultural farming system	Slash & burn with fertilizer/ manure & chemical application	Soil erosion, eutrophication & acidification due to fertilizer & chemical application.

Table 3: Characteristics of agronomic land use schemes in Ghana (Source: [4 p.4])

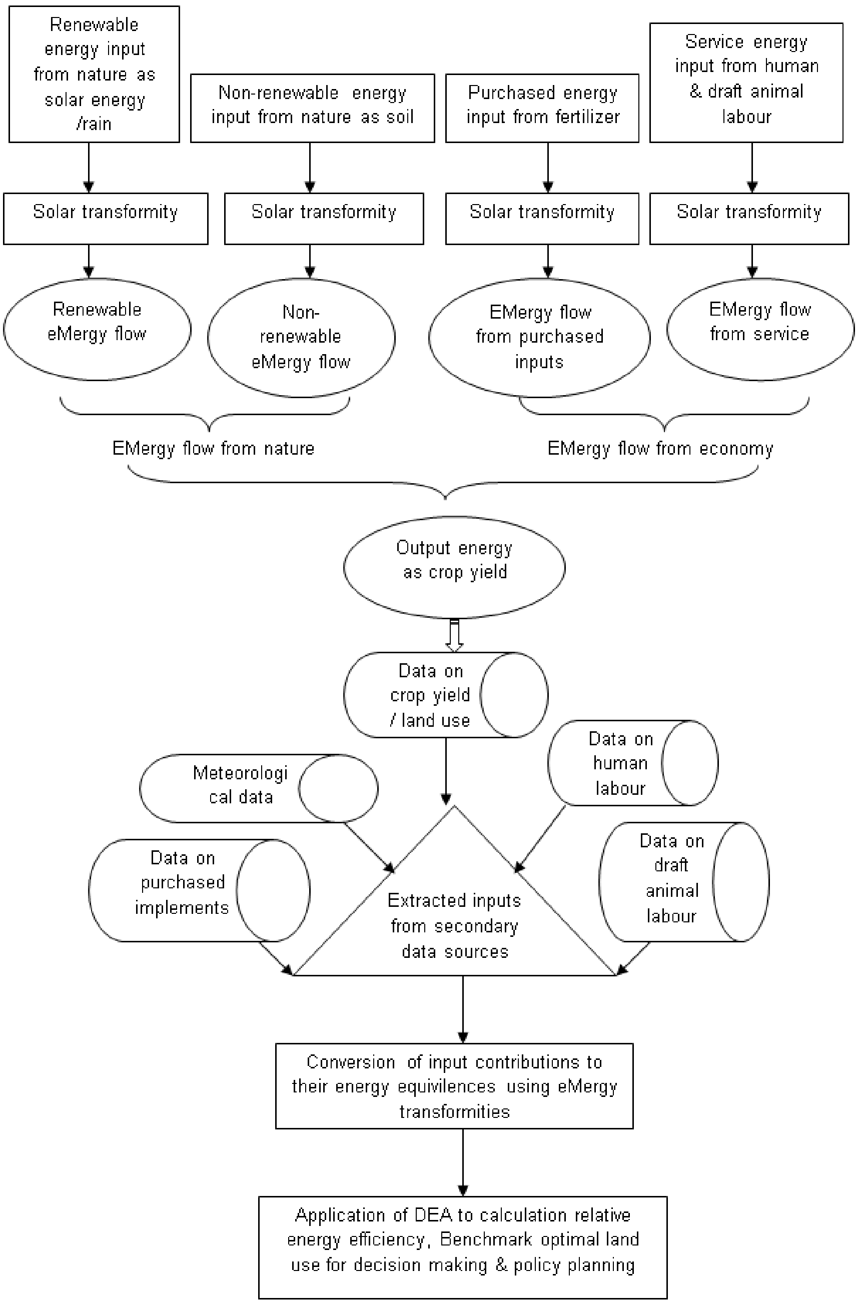

Figure 3: Conceptual framework

The eMergy component of the framework accounts for the various energy inputs to the production process in a given system. The energy use of the unit processes in the production system sum up to produce the output (yield). The inputs and outputs are converted to their energy values using transformity coefficients in eMergy. These energy values including their corresponding land-use schemes are fed into the DEA model component of the framework. The land-use schemes are the decision making units (DMUs). DEA uses a total factor productivity ratio to calculate the efficiency by attributing virtual weights to the input and output energy values. The performance of entities is then calculated using a linear optimisation process which maximises the ratio of each entity by finding the best set of weight for the entity. The optimisation is constrained by the fed data such that each entity is compared against the best observed performance. In this way, the best land-use can be benchmarked for decision making and policy planning that optimises energy use in agriculture.

In 1995, the FAO [5] had already highlighted the complexity involved in assessing energy efficiency in non-mechanised agricultural systems that employed human and draft animal power as input sources. In view of this complexity; our system boundary pays greater attention to direct inputs, and the produced outputs delivered at the farm gate. Transportation and agro-processing of output have not been considered in this framework. These limits have been adopted because of data constraints. Unlike in mechanised system where the embodied energy of machines is standard and energy is consumed only when a machine is at work the energy consumption of living systems (humans and draft animals) is continuous during their life span. Also, humans and animals need to be fed even when they are not momentarily expending energy at work. For this reason we further consider pasture land for animal grazing to be within the confinement of the system boundary in order to minimise the dependence of draft animals on the output energy (excluding crop residue). The other indirect inputs include energy used in the production of rudimentary farm implements and agro-chemicals. Figure 4 shows a sketch of an exemplary system boundary of a non-mechanised agricultural system.

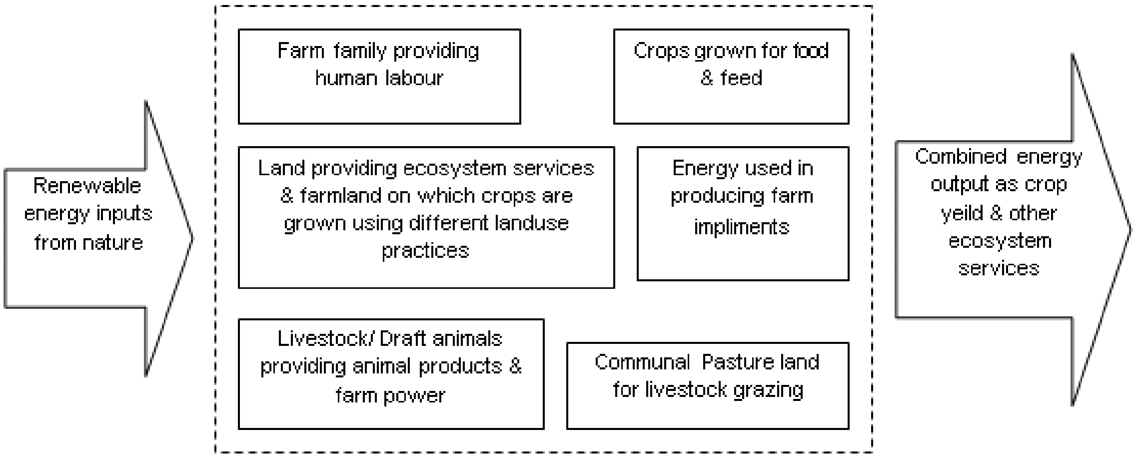

Figure 4: Sketch of system boundary

4. Discussion and conclusion

Following the oil crisis in the 1970s, the relationship between agriculture and energy (in this case fossil fuel) became vividly clearer and scholars have become increasingly aware of the dependence of agriculture on energy [20]. Since then, the analysis of energy use in agriculture has gained much momentum as many scholars have shown interest in the subject [26]. The main objective of a good energy analysis is to determine how much energy is actually needed to produce a given product or get a service done. But a more fundamental challenge is deciding upon a logical and consistent system boundary because different boundaries may lead to different results and conclusions [28].

The single ratio of output energy to input energy which defines energy efficiency obscures the visualisation of all the possible options through which the efficiency of a production system whose output depends on multiple inputs can be improved [2]. The method and framework in this paper presents therefore a unique approach that combines eMergy and DEA to account for farm energy efficiency in non-mechanised systems, and support for policy making from a sustainable development perspective. The eMergy component of the method and framework ensures that all fluxes are captured and sum to the total energy use [26]. It further considers input energy contributions from natural resources (sun, rain, wind) to man-made agricultural systems for the benefit of the farmer and therefore considers ecosystem services in agriculture. The DEA component of the framework increases the number of assessable alternative approaches that could be used to improve on efficiency by incorporating data from both renewable and non-renewable energy inputs including land-use. More interestingly is the scale sensitive approach of the framework to conduct assessment at regional scale. An assessment at regional scale will be useful in relating energy fluxes and balance to ecosystem services from both associated agricultural and naturally occurring ecosystems. The reference unit of SeJ further provides a means to compare different production systems in quantitative terms besides a qualitative approach.

Our future research tasks include fine-tuning the framework, and adapt it for assessing agricultural energy efficiency at regional scale, as well as to improve on the previewed weaknesses highlighted below. Some challenges include the paucity of reliable data on agricultural land use, crop yields, human and draft animal labour. Data are scantily documented in most developing African countries. DEA is a data oriented analysis approach. It does not require any prior assumptions on the underlying functional relationships in converting inputs into outputs. However, the advantage of not requiring such prior assumption can pose a weakness whenever over specialisation is the case. [12] caution that it can result to practically ignoring some inputs and outputs. Another current weakness may be related to the limits of the system boundary defined above. However, following [28] assessment at multiple levels minimises the problem of defending a particular system boundary.

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