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Sustainability assessment of wheat production using Emergy

Coppola, F.[1], Haugaard-Nielsen, H[2], Bastianoni, S.[1] & Østergård, H.[2]

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Abstract

Sustainability of crop production has to be given high priority when global biomass resources are limited. Here emergy evaluation is applied in order to assess sustainability of crop production exemplified by winter wheat. Emergy evaluation takes into account all inputs involved in a production system (i.e. renewable and non-renewable, local and imported) and transforms them into a common measure of direct and indirect solar energy requirement. The evaluation of winter wheat production is conducted by comparing conventional and organic management on two soil types using Danish reference conditions. The resource use efficiency of wheat production per kg biomass is higher using conventional management practices. This is due to high yield based on large use of non-renewable resources. The environmental loading ratio from organic management practices is about a third of the conventional implying that the organic management can be considered more sustainable.

Introduction

Increasing oil prices and foreseeable limitations of fossil resources has put emphasis on crops as a resource of raw materials for fuels and fibres in addition to their importance for food and feed. Also the many functions of crops in ecosystem services such as securing water reservoirs, biodiversity and landscape has been reconsidered. The crop resource is, however, limited since the inputs, which are needed for its production, are limited, e.g., fertiliser (organic or non-organic), fuel for machinery, human labour, as well as available land. In order to address the sustainability of crop production, assessments of material and energy flows are needed.

The concept of sustainability has many definitions all based on ensuring resources for future generations. Many sustainability assessments consider balances of energy and materials flows without qualifying to what extend the inputs are from renewable or non-renewable resources. The emergy evaluation methodology (Odum, 1996) emphasizes how to exploit renewable resources more efficiently such that the costly (with respect to resource limitations) non-renewables may last longer. The basis of emergy evaluation is the conversion of all process inputs, including energy from climatic resources like precipitation and global radiation, energy inherent in materials such as machinery and in services like human labour, into total amount of solar

1 Dept. of Chemical and Biosystems Sciences, Siena University, via della Diana, 2A, 53100 Siena, Italy. coppola12[a]unisi.it; bastianoni[a]unisi.it

2 Risø National Laboratory DTU, PO Box 49, 4000 Roskilde, Denmark. henrik.haugaard-nielsen[a]risoe.dk; hanne.oestergaard[a]risoe.dk (corresponding author)

energy by means of a conversion factor called transformity. In this way, all flows get the same common unit for the analysis.

Emergy has been used to assess sustainability of crop production in relation to bioenergy production (Bastianoni and Marchettini 1996), for comparison of different land uses (Lefroy and Rydberg, 2003) and to compare organic and conventional farming (e.g. Ortega *et al.* 2005). Here we describe the method and demonstrate its usefulness with four types of winter wheat production in Denmark: organic and conventional management on two locations with different soil types and climate.

Materials and methods

The present emergy assessment compares winter wheat production conducted under conventional and organic reference management practises on two Danish locations with slightly different climatic conditions; site I: sandy soil in south of Jutland and site II: sandy loam soil in east of Zealand. Data for inputs, field operations and yields were mainly obtained from farmers' advisory manuals (Dansk Landbrugsrådgivning 2003 and 2006), norms for direct and indirect energy consumption from Dalgaard *et al.* (2001), average actual evapotranspiration at similar sites from Barlebo *et al.* (2007) and global radiation from the Danish Meteorological Institute.

Emergy represents the solar energy used up directly or indirectly to make a product or to support a process; it is measured in sej (solar emergy joule). The basis of emergy evaluation is the conversion of all process inputs into emergy by means of the conversion factor transformity expressed in sej J^{-1} (emergy per Joule). When comparing two products from different processes, the product having the highest transformity requires most emergy (direct or indirect solar energy) for its production and is thus more costly. By definition, transformity of solar energy is equal to 1 sej J^{-1}. List of transformities are found in Emergy folios (2000-2002).

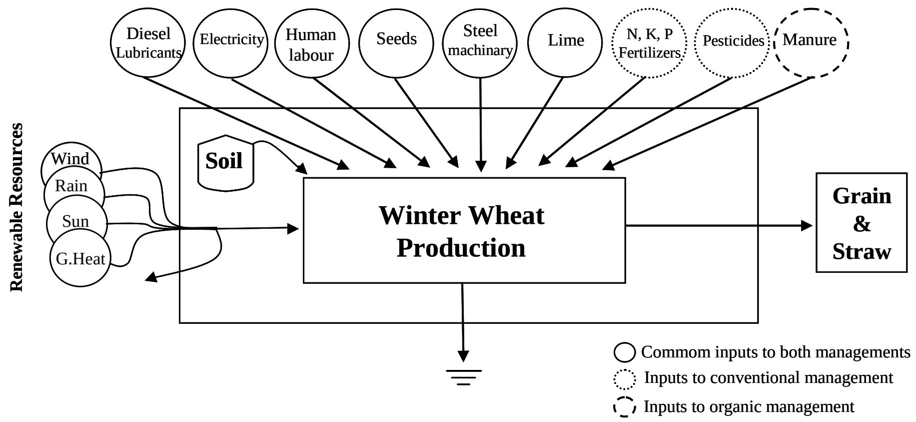

Figure 1: Energy System Diagram of organic and conventional winter wheat production

Flows of energy and matter for wheat production in Denmark were described by an Energy System Diagram (Figure 1) showing all resources contributing being i) renewables (R) such as sun, rain (only the amount evapotranspirated by crop), geothermal heat and wind, ii) local (within the system) non-renewables (N) such as soil, and iii) imported (from outside the system) non-renewables (F) such as fossil fuels, fertilizers, seeds and chemicals. Also the emergy based indicator Environmental Loading Ratio (ELR) was considered. This is the ratio of all non-renewable emergy flows both from inside and outside the system (N + F) to the renewable emergy flows

(R). The ELR is generally high for systems with a high level of technology and/or with high environmental pressure.

Results and discussion

For each system considered, a table with energy and material flows, transformities and resulting emergy flows was calculated for wheat grain and straw yield; here, only the summary of the calculations is shown (Table 1).

The crop yield increased about 2-fold between the four scenarios from the organic production on the sandy soil to the conventional on the sandy loam soil. The total annual emergy flow (e.g. total solar energy used up) per hectare had the highest value in the conventional management at both sites, implying that this production lead to a greater use of resources per hectare. In all scenarios, three inputs contributed substantially to the emergy flow: i) fertiliser application (manure approx $3x10^{15}$ sej ha^{-1} y^{-1} and synthetic fertiliser approx $4\text{-}5x10^{15}$ sej $ha^{-1}y^{-1}$ mainly from N fertiliser), ii) lime application (approx $0.8x10^{15}$ sej $ha^{-1}y^{-1}$) and iii) evapotranspiration (approx $0.7x10^{15}$ sej $ha^{-1}y^{-1}$). The difference between conventional and organic systems was mainly due to synthetic versus organic fertiliser use. The two sites differed by higher input of synthetic fertiliser at site II compared to site I and higher evapotranspiration at site I compared to site II (480 and 420 mm y^{-1}, respectively).

Table 1: Summary of Emergy assessment of winter wheat grain and straw production for organic and conventional management at different sites

	Sandy soil, site I		Sandy loamy soil, site II	
	Organic	Conventional	Organic	Conventional
Total dry matter (t ha^{-1} y^{-1})	5.6	8.0	8.2	12.4
Total emergy flow (sej ha^{-1} y^{-1})	$5.6x10^{15}$	$6.6x10^{15}$	$5.4x10^{15}$	$6.9x10^{15}$
Transformity wheat crop (sej J^{-1})	$7.1x10^{4}$	$5.8x10^{4}$	$4.6x10^{4}$	$3.9x10^{4}$
Environmental Loading Ratio	2.3	7.3	2.4	8.5

The transformity values indicate the use of solar energy related to the energy of the final product. These values decrease from organic production on sandy soil to conventional production on sandy loam soil corresponding inversely to the increase in yield. This implies that the efficiency of the production system per unit biomass is higher using conventional management practises. However, this efficiency is caused by the much larger use of non-renewable resources as seen from the Environmental Loading Ratio (ELR); ELR is more than 3 times higher as compared to organic management practices. This implies that under these growing conditions the organic management needs much less non-renewable inputs.

So far, the analysis has considered the total crop biomass (grain + straw); traditionally, only grain is considered. If this was the case in the present study, all emergy flows would be accounted for in the production of the grain giving somewhat higher values. The highest efficiency per kg (or Joule) as seen from the transformity for grain would again be for conventional production on sandy loam soil ($6.1x10^{4}$ sej J^{-1}), and the average value over all systems would be $8.6x10^{4}$ sej J^{-1}. The latter value is a little lower than the average transformity value for winter wheat production in Italy ($15.9x10^{4}$ sej J^{-1}, Ulgiati et *al.*, 1994) and nearly similar to the Siena Province value ($11.3x10^{4}$ sej J^{-1}, Bastianoni et *al.*, 2001). Such differences may be due to a more efficient production in Denmark primarily caused by a higher grain yield potential. Unfortunately, no other published transformity values could be found for comparison.

Wheat straw is, however, also a valuable raw material: i) if we consider the straw as residual biomass usable as feedback in the wheat production systems (e.g. to generate electricity for grain drying), the transformity of product output (wheat grain) would decrease; ii) if the straw is left in the fields as a carbon source we would have an increase in soil fertility and a feedback potentially improving subsequent crop production. A detailed analysis of the role of straw as raw material for energy purposes and/or bio-fertilizers is under preparation.

Conclusions

This emergy evaluation of winter wheat production conducted under Danish reference growing conditions concluded that organic production (sandy loamy soil) was the most favorable growing system due to the lowest ELR value. However, the best efficiency of the resource use per kg biomass (lowest transformity value) was obtained on the rather fertile sandy loamy soils on east Zealand and highest for the conventional management due to high yield based on large use of non-renewable resources. We see emergy assessment as a tool to emphasize the use of natural and especially renewable resources, and an accounting method where environmental costs are evaluated using a common scale for all energy and materials flows, i.e., the direct and indirect solar energy used up to obtain a product.

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