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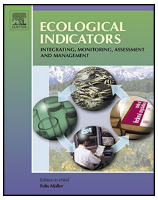

Renewability and emergy footprint at different spatial scales for innovative food systems in Europe

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ABSTRACT

Food production is increasingly being challenged by limited resources of energy and land as well as by growing demand for food. In a future with less availability of fossil fuels, land area will become very important for capturing the flow-limited renewable resources. Emergy assessment has been applied to calculate scale dependent indicators, which account for the land area needed, if agricultural systems were to be supported solely on renewable sources. These indicators are designated emergy footprints (EmFs) and expand the concept of support area defined previously in emergy accounting. The EmF (in ha) is calculated based on renewable empower densities which convert resource use into area equivalents able to capture renewable flows. The spatial division between on-site, local and non-local land areas applied in this study, identifies where the support area is located in order to apply a site-specific renewable empower density. A new indicator applying the EmF is the emergy overshoot factor, which estimates the ratio between EmF and the geographical system boundary (in ha). We apply this approach on three innovative food supply systems in Europe located at farms characterised by combining high diversity, reduced use of resources, nutrient cycling and local sales. The question is whether this type of food system may be considered sustainable from a resource use point of view measured as resource use efficiency by means of unit emergy value (UEV), renewability ($R_{\text{on-site}}$ and R_{global}), direct and indirect occupation of land on different spatial scales (EmF and Emergy overshoot factor) and productivity per ha of the directly observed areas and the EmF area, respectively. Labour inputs constituted between 13 and 80% of the total emergy flow. The proportion of resource use from renewable sources was between 31 and 60% when excluding the inputs of direct labour. The food system with the lowest UEV, excluding direct labour, had the highest emergy overshoot factor, which even exceeded the global average of seven. However, this system had the highest productivity. The system with the highest UEV, excluding direct labour, had the lowest overshoot factor. In conclusion, each food system strategy has its pros and cons and it depends on the priorities, which is judged the most sustainable from an emergy point of view.

1. Introduction

In most of the 20th century the main focus for food production has been to increase yields to meet the demand of growing populations (Gomiero et al., 2011). Consequently, modern food systems (production and distribution) are heavily dependent on fossil energy and other non-renewable resources as exemplified by the Danish food system (Markussen and Østergård, 2013). More sustainable alternatives to industrialised large scale monocultures, which have been dominating agricultural production during the past century, need to be accessed (Godfray et al., 2010). Agriculture is not only a matter of producing food but also a way to manage nature. For example agricultural production systems, which are mainly supported from a local resource base, reduce the use of resources associated with transportation of traded goods, maintain a healthy nutrient recycling and reveal the negative environmental impacts for the consumers (Bouwman and Booij, 1998; Grote et al., 2005; Sundkvist et al., 2005). In addition, direct selling to consumers has been identified as a driving force for increasing on-farm diversity (Bjørklund et al., 2009). Future food production must increasingly focus on system functioning and use of renewable resources as well as local recycling in order to survive within the constraints of reduced availability of fossil fuels (Godfray et al., 2010). In the wake of this challenge, land is increasingly becoming a valuable and limited resource, and this trend will increase in a future more dependent on renewable energy (Pimentel et al., 2010; Scheidel and Sorman, 2012; Sorman and Giampietro, 2013).

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Agricultural systems operate at the interface between nature and society. These are dependent on local, renewable flows of rain, wind and geothermal heat, on local, non-renewable flows of e.g. ground water and soil organic matter as well as on material and labour inputs from society. Emergy assessment is an upstream assessment tool accounting for all available energy inputs used and degraded in the process of making a product or service (Odum, 1996). It emphasise the distinction between renewable resources, which are flow-limited, and non-renewable resources, which are stock-limited. It may also distinguish between resource use at different spatial scales being on-site, local and non-local (Wright and Østergård, 2015) or in general between local and global resources (e.g. Ulgiati and Brown, 2014).

The use of renewable flows is limited by the available area to capture them. Therefore, land is the limiting factor and sustainability indicators measuring use of land are required. The Ecological Footprint (EF) is such an indicator (Wackernagel and Rees, 1996) and it has been widely applied e.g. via the Global Footprint Network (footprint.org). It calculates a virtual bioproductive area (in global hectares, gha) reflecting the area needed for consumption and for waste (CO_2) processing of a person, a country or globally. EF is related to the biocapacity (BC), i.e. the actual bioproductive area of the same region, and an ecological overshoot is obtained if EF is bigger than BC. A potential overshoot may be indicated by the number of Earths it would take to support humanity's EF if everyone lived like an average citizen of a given region. Using this planet equivalents indicator, approx. 1.5 planet Earths are necessary to sustain the present global consumption (Global Footprint Network, 2015). In all these calculations, only bioproductive area (e.g. land, marine and inland water able to perform photosynthesis and produce biomass) is included and it is recalculated every year. This ignores the importance of non-bioproductive area including the oceans for the overall cycles of carbon, nutrients and water on earth (Cuadra and Björklund, 2007; Pereira and Ortega, 2012; Zhao et al., 2005).

There have been several suggestions for converting the values of an emergy analysis into equivalents of land starting from year 2000 (Wackernagel and Yount, 2000). An emergy-based footprint was defined by Björklund and Johansson (2013) which calculates the theoretical area needed, if all resources used in a production system were generated by local, renewable resources. This approach has also been presented as support area or region (Agostinho and Pereira, 2013; Brown and Ulgiati, 2001; Huang and Chen, 2005). Another approach to study the consumption of countries by relating emergy flows to land use categorising consumption as in EF has been developed by Zhao et al. (2005). It was reformulated by Siche et al. (2010) and Pereira and Ortega (2012) who defined the footprint as consumption of emergy per capita per year relative to the global empower density per year. Unfortunately, they described their footprint in the unit gha which is very different from the unit gha used in EF. In contrast to EF, the footprint of Zhao et al. (2005) does not require a definition of productive land or a consideration of the variability of yields between land types.

The aim of this paper is two-fold. At first, to formalise the decomposition of the emergy footprint indicator based on renewability empower densities at different spatial scales and define an emergy overshoot factor representing an important aspect of environmental sustainability. Secondly, to evaluate, by applying this methodology, the sustainability of three case studies representing innovative food supply systems. The food supply systems are located at farms characterised by combining high diversity, reduced use of resources, nutrient cycling and local sales. These adopted methods take advantage of representing resource use as land area to be able to demonstrate that the direct use of land area for production may only be a small proportion of the actual land area used and even a smaller proportion of the land area required if all consumption was based on renewable resources.

2. Theory – emergy analysis

Emergy analysis is a quantitative evaluation tool that determines all flows of available energy supporting a system. Emergy is often referred to as 'energy memory', as it is the available energy (exergy) used up directly or indirectly in transforming one kind of energy to another (Odum, 1996). We refer to its unit as solar equivalent joule, abbreviated seJ (Brown and Ulgiati, 2015). The approach includes free available flows from nature (sun, wind, rain, and geothermal heat), non-renewable inputs (e.g. oil, materials, groundwater or any other environmental resource used up faster than it is replaced) as well as inputs from society which are direct labour and services (indirect labour). The approach is very suitable for evaluating processes working at the interface of nature and society, including services from nature as well as services from society (labour). All inputs to a system are multiplied by a unit emergy value (UEV) to calculate the corresponding use of emergy and all flows are summed to account for the total emergy use of the system. The UEV is calculated by dividing the total emergy use in the production process by the available energy of the output, here the food energy in joules. All UEVs have been converted to the baseline 15.83E+24 seJ/year (Odum, 2000).

2.1. Spatial division of inputs

Two classes of inputs constituting renewable (R) and non-renewable (N) flows, respectively, are accounted for within the defined system boundary, i.e. the area of the farm. Inputs from outside the system boundary, characterised by being purchased, external inputs, are classified as F and they consist of the same types of flows (R and N) now at the location of production. This structure may be iterated backwards for all stages of the production chain. Therefore, F may be written as a sum of inputs being renewable at a global scale and non-renewable at a global scale. As R represents renewable inputs to a product or service, the ratio R/U can be considered the renewability fraction (or just renewability) of the system's total emergy use, U. This renewability should be included in calculations up through the production chain. Accounting for renewability in inputs from outside the system boundary by distinguishing local and non-local inputs is increasingly being recognised as an improvement of the emergy methodology (Agostinho and Ortega, 2012; Cavalett and Ortega, 2009; Cavalett et al., 2006; Felix and Tilley, 2009; Kamp and Østergård, 2013; Ulgiati and Brown, 2014; Ulgiati et al., 2005; Wright and Østergård, 2015).

We define the spatial origin of the inputs following the nomenclature in Wright and Østergård (2015). Inputs consist of '*on-site*' resources defined as resources from the area within the geographical system boundary i.e. the production site area, '*local*' resources defined as resources from the neighbourhood area outside the geographical system boundaries (i.e. inputs from the neighbours or inputs managed locally, i.e. from the 'terroir') and '*non-local*' resources originating from outside the two mentioned areas. All together, they constitute the total or *global* resources used. The corresponding renewable and non-renewable inputs (six in total) are designated R_j and N_j, respectively, where j = on-site, local and non-local. R_{global} and N_{global} are the respective sums of the three categories.

By definition, $R_{\text{on-site}} = R$ and $N_{\text{on-site}} = N$. Emergy flows from the remaining four classes of inputs add up to F. For each input to F, its origin (local or non-local) is determined. Then from the literature, its on-site renewability fraction at its location of origin is applied to estimate the contribution to R_j and its contribution to N_{j}