The Material and Energy Basis of Rome (Italy). An Investigation of Direct and Indirect Resource Use by Means of Material Flow, Energy and Footprint Methods

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Supporting Information

Description of the evaluation methods integrated within the SUMMA framework

1. Upstream methods

The Material Flow Accounting method (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998; Bargigli, 2004; Bargigli et al., 2004) is aimed at evaluating the environmental disturbance associated with the withdrawal or divertion of material flows of resources from their natural ecosystemic pathways. In this method, each input is multiplied by an appropriate Material Intensity factor (g/unit), respectively accounting for the total amount of abiotic matter, water, air and biotic matter that is directly or indirectly required in order to provide that very same input to the system. The resulting indirect material flow of the individual inputs are then separately summed together for each environmental compartment (again: abiotic matter, water, air and biotic matter), and assigned to the system's output as a quantitative measure of its cumulative upstream environmental burden from that compartment (often referred to as "Ecological Rucksack").

The Embodied Energy Analysis method (Slesser, 1974; Herendeen, 1998) deals with the gross (direct and indirect) commercial energy requirement of the analysed system, and offers useful insight into the first-law energy efficiency of the analysed system on the global scale, taking into consideration all the employed commercial energy supplies. In this method, all the material and energy inputs to the analysed system are multiplied by appropriate Oil Equivalent Factors (g_{oil}/unit), and the cumulative embodied energy requirement of the system's output is then computed as the sum of the individual Oil Equivalents of the input flows, which can be converted to energy units by

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multiplying by the standard calorific value of 1 g of oil (41,860 J/g). The chosen cumulative indicator is the so-called "Gross Energy Requirement" (GER), expressing the total commercial energy requirement of one unit of output in terms of equivalent Joules of petroleum oil.

The Emergy Synthesis method (Odum, 1988; Odum, 1996; Brown and Ulgiati, 2004) also looks at the environmental performance of the system on the global scale, but in addition to commercial flows of energy and materials it takes into account all the free environmental inputs such as sunlight, wind, rain, driving important biosphere services such as dilution and uptake of pollutants, water cycle, biodiversity, etc., as well as the indirect environmental support embodied in human labour and services. The latter are usually not included in traditional embodied energy analyses. Moreover, the accounting is extended back in time to include the environmental work needed for resource formation. Therefore, emergy accounting expands its focus over space and time, in order to capture at least in principle the whole dynamics of biosphere activities. The total emergy requirement can be interpreted as an indicator of the total appropriation of environmental services by the analysed human activity[2]. In particular, while the total *non-renewable* emergy input to the system under study provides a quantitative estimate of global non-renewable resource depletion, the total *renewable* emergy requirement is a measure of all the natural exchange-pool resources that are diverted from their natural pathways, and that can therefore no longer provide their natural ecosystemic functions. The ecological relevance of the emergy methodology was recently discussed in detail in a Special Issue of the International Journal of Ecological Modelling, volume 178, where the scientific career of H.T. Odum is illustrated.

Finally, *Ecological Footprint* is expressed as the amount of productive surface that is needed to sustain a given population (Wackernagel and Rees, 1996) in all of its needs (food, housing, fresh water, environmental services). The method, which could be considered a simplified version of the emergy accounting method, converts the consumption of energy, resources and environmental services, either per capita and on the national scale of a country, into the amount of *actual* or *virtual hectares* needed to supply them (for instance, the amount of hectares per person needed to supply food, fibres, construction material). Fossil energy use is accounted for in terms of the hectares of photosynthetic activity (e.g.: new forest biomass) needed to uptake the CO_2 released by fuel use. A similar accounting procedure applies to the use of minerals (fuel for extraction and processing as well as water needed in the process). Further info as well as national accounts are available online at http://www.footprintnetwork.org.

[2] The same concept and rationale applies to non-living phenomena (e.g. rain formation) as well as to processes supporting living systems other than humans and human societies. In this paper we focus on cities and therefore mainly consider the dynamics of human dominated processes.

Despite sharing a common focus on resource depletion, the selected upstream methods offer different and complementary perspectives. In particular, Material Flow Accounting (MFA) and Emergy Synthesis both entail a large-scale donor-side point of view, whereby the analysed system is seen as a sort of “funnel” into which environmental resources are made to converge and are finally degraded. The main difference between the two is that MFA is strictly concerned with the material resources that are necessary to support the process, and thus is a good proxy for the immediate environmental harm caused by the extraction, transportation and processing of the resources themselves. Instead, Emergy Synthesis takes one further step back and looks at the process under study from the point of view that all the inputs to a process have at some time required a certain amount of the ultimate energy resources that drive the Earth’s cycles: i.e. sunlight, geothermal heat and gravitational potential. This translates into a method that is more apt to highlight the long-term sustainability of a system, also taking into account the exploitation of those energy resources that are not part of the mass flows (either because they have no mass – i.e. sunlight, or because they are no longer there, but were used up in the past in order to make another resource available). The Ecological Footprint method places larger focus on direct and indirect photosynthetic activity, either for food and photosynthetic materials production and for the uptake of CO_2 generated by human use of fossil fuels. In so doing, the importance of food supply and fuel use is very likely overestimated, compared with other important flows such as minerals.

The Embodied Energy approach, on the other hand, is centred on the pivotal concept of First Law efficiency, and has a more direct relationship with the market logic. In particular, the method is concerned with the employment of commercial energy resources, both as direct inputs and as indirect upstream requirement, and thus provides a good overall indication of the intensity of the addiction of a productive system or a process to use of fossil fuel reserves.

2. Downstream method

In SUMMA, a set of crucial downstream impacts are assessed by means of the calculations of the potential environmental damage of airborne, liquid and solid emissions by means of appropriate equivalence factors to selected reference compounds for a large set of impact categories. The impact potential of the analysed system for each category is calculated by multiplying all emissions by their respective impact equivalence factors, and then summing the results, according to LCA-Life Cycle Assessment procedures internationally agreed upon (ISO, 1997; ISO, 1998). However, for the sake of clarity, in this paper we use a simplified approach, which only accounts for selected emissions generated by a city’s social and economic dynamics (emissions per person and per unit GDP). In particular, we focus here mainly on emissions involved in global warming and acidification potential. Comparison is also drawn between local and global scales emissions, in order to account for processes occurring (and generating environmental load) far from the investigated system.

Tables of Intensity Factors used for the quantitative evaluation

Table S1 Material Intensity factors per unit of product

Item	Abiotic	Water	unit	Reference
Top soil (erosion, processing, etc)	0.76	0.20	g/g	Odum 1996
Gasoline	1.36	9.70	g/g	www.wuppertal.de
Diesel fuel	1.36	9.70	g/g	www.wuppertal.de
LPG (Liquid Petroleum Gas)	1.36	9.70	g/g	www.wuppertal.de
Heavy oil for domestic heating	1.43	10.40	g/g	www.wuppertal.de
Natural gas				
Domestic use for cooking	1.22	0.50	g/g	www.wuppertal.de
Domestic use for heating	1.22	0.50	g/g	www.wuppertal.de
Other uses	1.22	0.50	g/g	www.wuppertal.de
Electricity	4.39E-04	1.77E-02	g/J	www.wuppertal.de
Water (from aqueduct)		1.00	g/g	By definition
Main Food Items				
Fish	1.30		g/g	Abiotic: from Wuppertal paper 114, 2001, Nickel et al. p. 36
Meat	16.70	533	g/g	Abiotic: from Wuppertal paper 114, 2001, Nickel et al. p. 36. Water: Our calculation
Fruits and Vegetables	1.40	950	g/g	Abiotic: from Wuppertal paper 114, 2001, Nickel et al. p. 36. Water: our calculation.
Milk, cheese and other derivatives	6.60	533	g/g	Abiotic: from Wuppertal paper 114, 2001 Nickel et al. p. 36. Water: Our calculation.
Cereals and derivatives	2.49	950	g/g	Abiotic: from Wuppertal paper 114, 2001, Nickel et al. p. 36. Water: our calculation.
Wine and alcoholics	n.a.	500	g/g	Water: conservative assumption, based on water demand for grape-to-wine processing
Olive and seed oils	14.03	22.34	g/g	Our calculation
Steel and iron	10.97	135.85	g/g	www.wuppertal.de
Copper	179.07	236.39	g/g	www.wuppertal.de
Aluminium	18.98	539.20	g/g	www.wuppertal.de
Cement (Portland)	3.22	16.90	g/g	www.wuppertal.de
Rocks and Sediments	2,11	7,95	g/g	www.wuppertal.de
Glass	2.95	11.60	g/g	www.wuppertal.de
Plastics	4.90	269.50	g/g	www.wuppertal.de
Asphalt	1.36	9.70	g/g	www.wuppertal.de
Chemicals	4.13	122.03	g/g	www.wuppertal.de
Wood	1.39	21.80	g/g	www.wuppertal.de
Textiles	8.35	1987.75	g/g	www.wuppertal.de
Paper and derivatives	3.36	124.04	g/g	www.wuppertal.de
Fertilizers	6.02	38.77	g/g	www.wuppertal.de

Table S2 Energy intensity factors (grams of oil equivalent/unit of item)			
Item	**Value**	**unit**	**Reference**
Gasoline	1.50	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Diesel fuel	1.28	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
LPG (Liquid Petroleum Gas)	1.41	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Heavy oil for domestic heating	1.23	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Natural gas			
Domestic use for cooking	1.15	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Smil (1991), Bargigli et al., 2004
Domestic use for heating	1.15	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Smil (1991), Bargigli et al., 2004
Other uses	1.15	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Smil (1991), Bargigli et al., 2004
Electricity	59.7	g_{oil}/MJ	Brown and Ulgiati, 2002
Water (from acqueduct)	0.13	g_{oil}/kg	Smil, 1991
Main Food Items			
Fish	0.92	g_{oil}/g	Russo et al., 2004
Meat	0.98	g_{oil}/g	Biondi et al., 1989
Fruits and Vegetables	0.06	g_{oil}/g	Biondi et al., 1989
Milk, cheese and other derivatives	0.23	g_{oil}/g	Biondi et al., 1989
Cereals and derivatives	0.14	g_{oil}/g	Biondi et al., 1989
Wine and alcoholics	0.01	g_{oil}/g	Biondi et al., 1989
Olive and seed oils	0.05	g_{oil}/g	Biondi et al., 1989
Steel and iron	0.69	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Copper	2.21	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Aluminium	6.80	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Cement (Portland)	0.17	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Rocks and Sediments	0.0020903	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)

Glass	0.63	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Plastics	2.25	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Asphalt	3.87	g_{oil}/g	Our calculation, based on nafta value: from Boustead and Hancock, 1979, pag 347
Chemicals	2.25	g_{oil}/g	Assumed equal to plastics; conservative estimate
Wood	0.12	g_{oil}/g	Smil (1991)
Textiles	5.05	g_{oil}/g	Nieminen et al., 2007
Paper and derivatives	0.90	g_{oil}/g	Our calculation after Boustead & Hanckock (1979), Jarach (1985) and Smil (1991)
Fertilizers	0.76	g_{oil}/g	Biondi et al., 1989

Table S3 Emission factors of fuel combustion								
Fuel used	**Emissions from fuel combustion (g/MJ of fuel fired)**							
	HC (*)	CO	NO_x	Particulate	SO_2	CH_4	N_2O	CO_2
Natural gas (used in domestic sector, heating and cooking)	6.5E-4	0.019	0.086	0.0014	2.9E-4	1.3E-4	2.0E-4	56.6
Natural gas in turbine	0.0014	0.069	0.052	9.7E-4	2.9E-4	0.0046	0.0019	56.5
Heavy Fuel Oil in industrial boilers	8.6E-4	0.015	0.051	0.0058	0.15	0.0031	3.4E-4	78.4
Gasoline in engines	0.835	1.08	0.09	0.0033	(**)	(§)	9.7E-3	70.67
Diesel in engines	0.09	0.27	1.02	0.07	(**)	(§)	6.8E-4	70.99
LPG in engines	n.a.	1.65	0.70	0.02	(**)	(§)	4.1E-3	64.57

(*) unburnt hydrocarbons, except CH_4
(**) assumed desulphurized fuel
(§) added to “unburnt hydrocarbons”
Sources: www.apat.gov.it; EPA document, 'Compilation of air pollutant emission factors', Volume I, fifth edition, point sources AP-42 (http://epa.gov/); Corinair (1993); http://www.pre.nl/simapro/; and Authors' calculations based on combustion stoichiometry.

Table S4 Demand for Productive land (Ecological Footprint intensities)			
Item	**Value**	**Unit**	**Reference**
Land for uptake of CO_2 released by fuel combustion	1.79E-04	Ha/kg	Estimated from energy intensity and photosynthesis average data
Land for production of main food items:			
Fish	4.17E-02	Ha/kg	Wackernagel and Rees, 2001, page 188
Meat	2.04E-02	Ha/kg	Wackernagel and Rees, 2001, page 188
Fruits and Vegetables	5.56E-05	Ha/kg	Wackernagel and Rees, 2001, page 188
Milk, cheese and other derivatives	1.34E-03	Ha/kg	Wackernagel and Rees, 2001, page 188
Cereals and derivatives	3.64E-04	Ha/kg	Wackernagel and Rees, 2001, page 188
Wine and alcoholics	1.18E-03	Ha/kg	Our calculation from ISTAT, 2002
Olive and seed oils	1.67E-03	Ha/kg	Our calculation from ISTAT, 2002
Wood (agric. prod only) (*)	8.06E-05	Ha/kg	Our calculation from primary production of two different kinds of local forest
Textile fibers (agric. prod. only) (*)	1.00E-03	Ha/kg	Wackernagel and Rees, 2001, pag 188
Paper and derivatives (as wood equivalent) (*)	3.23E-04	Ha/kg	Our calculation from energy intensity of wood

(*) Only land for production of biomass is included here. Additional land for uptake of CO2 released in the process must be accounted for separately.

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