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# Emergy-based mid-point valuation of ecosystem goods and services for life cycle impact assessment

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## Key words:

Ecosystem goods and services;  
emergy; characterization factor  
(CF); life cycle assessment (LCA); life  
cycle impact assessment (LCIA);  
resource; unit emergy value (UEV)

**Abstract** – Ecosystem goods and services (EGSs) are of crucial importance for the economic and social development of human communities. The well-established life cycle assessment (LCA) method is facing a number of challenging improvements to define new Characterization factors (CFs) for life cycle impact assessment (LCIA) of EGSs. Very recently, extensive work conducted under the UNEP/SETAC Life Cycle initiative has been completed with the goal of providing new LCIA methods and spatially differentiated mid-point CFs for land use and land use change impacts on biodiversity and ecosystem services. However, the implemented models do not enable one to assess the actual damage to ecosystem functionality, and thus the relationship among EGSs and related areas of protection (e.g. AoP of “Natural Resources”) remains undefined. This paper aims at investigating the potential characterization ability of the Emergy method for LCIA of EGSs. The goal is to use the extensive libraries of Unit Emergy Values (UEVs) of primary services and resources as CFs for LCIA to evaluate the physical contribution of EGSs in supporting life cycle processes. Having its roots in thermodynamics and systems ecology, Emergy can appraise a larger and more diversified (than LCA) number of EGSs through a common physical denominator, i.e. the solar emjoule or seJ, which measures the solar energy embodied in natural products. Emergy thus has a typical Nature-oriented perspective, accounting for the available energy that is used up by the natural cycles, directly and indirectly, to generate biotic and abiotic resources. A library of selected UEVs (more than 100) for biophysical EGS valuation has been framed including values collected from the Emergy literature and formulated on the latest planetary baseline (i.e.  $15.2E + 24 \text{ seJ/yr}$ ). Advantages and limitations for future application of these values toward an LCIA mid-point impact characterization of Emergy are discussed. UEVs may represent mid-point LCIA factors for ecological contribution analysis, enabling one to account for the memory of energy previously required to produce EGSs, which can be used as a proxy to assess the future environmental work necessary to regenerate the used EGSs. However, the added value of Emergy for LCA is still debated, mainly because of the low accuracy and unclear meaning of the UEVs in relation to the availability of resources. Therefore, Emergy can be conceived as a suitable physical measure complementary to the economic valuations and current “user-side” tools applied in LCA.

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## 1 Introduction

The Millennium Ecosystem Assessment, which is the worldwide reference and most comprehensive survey presenting the state of Earth's ecosystems, defines and classifies the ecosystem goods and services (EGSs) into four domains as follows [1]: *provisioning* services (i.e. products directly obtained from ecosystems, e.g. freshwater, fossil fuels and minerals, timber, food, genetic resources

and wild plants, natural medicines), *supporting* services (i.e. services required to deliver and support all the other ecosystem services, e.g. soil formation, primary production, photosynthesis, nutrient cycling), *regulating* services (i.e. benefits obtained from the regulation of ecosystem processes, e.g. air quality regulation, water purification and regulation, climate regulation, erosion regulation, pest and disease regulation, pollination, carbon sequestration), and *cultural*

## List of acronyms

AoP	Areas of Protection
CFs	Characterization Factors
EGSs	Ecosystem Goods and Services
Em\$	Emdollars
EmR	Emergy-to-money Ratio
ESV	Ecosystem Services Valuation
GDP	Gross Domestic Product
HH	Human Health
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
NE	Natural Environment
NR	Natural Resources
PDF	Potentially Disappeared Fraction
UEV	Unit Emergy Value

services (i.e. cultural, spiritual, religious, recreational and other non-material benefits people may obtain from ecosystems).

Whereas EGSs are of crucial importance for the production of commodities and for the economic and social development of human communities [2, 3], their value accounting is usually neglected by the conventional economic and social-based indicators (e.g. Gross Domestic Product-GDP) and also by the most used environmental impact assessment methodologies, such as Life Cycle Assessment (LCA).

LCA is a widely accepted and standardized methodology to evaluate the life cycle environmental impacts of systems and products [4,5]. The Life Cycle Impact Assessment (LCIA) is the downstream phase of a LCA where the life cycle inventoried environmental interventions (i.e. elementary flows of resource extractions and pollutant emissions modeled within the Life Cycle Inventory-LCI phase) are converted to potential impacts and damage through the use of specific Characterization Factors (CFs).

The LCA method is facing a number of challenging improvements to define new CFs for LCIA at the mid-point (potential impact) and/or end-point (damage) levels of the cause-effect chain. The LCIA reflects the values defined as three areas of protection (AoP): “Human Health” (HH), “Natural Resources” (NR) and “Natural Environment” (NE) [4, 6]. Whereas there is a general

acceptance on the scope of the first AoP, the evaluation of NR and NE remains a highly debatable issue. A clear distinction between these two AoP does not exist, because they are intrinsically linked [6,7]. The extraction of resources, such as mineral deposits, fossil energy carriers, fish, trees and water has many repercussions on the environment. The extracting activity in itself (e.g. mining, forestry, fishery) can also release toxic emissions, create noise, damage the landscape, etc., which are dealt with under other AoP [6]. Moreover, the definition of the NR AoP has not yet been properly formulated, because it may rely upon several issues. First, it is not clear whether the damage should be evaluated only for the removal of resources that are necessary for human purposes (i.e. anthropocentric and utilitarian perspective) or should also include aspects of protection for the other species and ecosystems (i.e. Nature-oriented perspective). For instance, while humans could live without trees in some regions, squirrels and other mammals and insects cannot survive without the existence of trees [6]. Second, there are high degrees of uncertainty in forecasting future availability of resources and functioning of ecosystem services, which have inherent effects on their scarcity and damage. This is basically due to partial agreement and/or scarce knowledge about future technologies of extraction and resource consumption behaviors, which mostly depend on the human population growth and needs in developing countries. The AoP of NR is therefore addressed to assess the damage to the productivity of the ecosystems, i.e. the damage to resources or ecosystem goods.

Accordingly, several LCIA indicators have been developed to evaluate the role of resources for human purposes e.g. [8–15]. The most recommended approach is based on the notion of scarcity, which is assessed by evaluating the future marginal cost of extraction/use of the resources [14, 15]. Basically, it is assumed that extracting a high concentration of resources today will force future generations to extract a lower concentration or lower value resources [6]. This results in the need for additional efforts, i.e. higher energy or costs, which leads to an

increased impact on the environment and economy [6, 14, 15]. With regard to the AoP of NE, the aim is to quantify the negative effects on the function and structure of natural ecosystems as a consequence of exposure to chemicals or physical interventions [6]. This end-point impact is usually addressed by applying the potentially disappeared fraction (PDF) of species, which is the recommended indicator to quantify the loss of biodiversity due to chemical exposure [6]. However, the PDF indirectly depends on the Land Use (LU), which is a mid-point impact category that may also be used to account for the availability of resources, thus influencing the AoP of NR. Indeed, the LU reflects the damage to ecosystems due to the effects of occupation and transformation of land [6] and is currently considered as the starting point to improve the approach of EGSs evaluation in LCA.

Very recently, comprehensive work conducted under the UNEP/SETAC Life Cycle initiative [16] has been completed with the goal of providing a set of LCIA methods and spatially differentiated CFs for LU (i.e. land occupation) and LU change (i.e. land transformation) impacts on biodiversity and ecosystem services in a comprehensive way to assess e.g. biodiversity damage [17], climate regulation [18], biotic production [19], erosion and freshwater regulation, and water purification potential [20]. Despite this great effort, however, the implemented methods still only assess a “potential” impact at the mid-point level, whereas the actual damage to ecosystem functionality and productivity and the relation between different EGSs and the AoP of NR and NE remain undefined and a challenge to achieve. One of the main goals reached by the UNEP/SETAC Life Cycle initiative is the definition, harmonization and ranking of a large set of LU and LU change elementary flows created as a common inventory database for both global and local assessments. This is undoubtedly a great achievement toward a standardized classification and regionalization of LU inventories and impact assessment methods, because it provides for the first time the necessary flexibility to providers of inventories and to developers of impact assessment methods

and overcomes the problems of mismatching definitions between the two [21]. However, the LCA method also shows weak points related to the completeness of inventory for EGSs. Conventionally, the evaluation of EGSs in LCA has been focused only on a few *provisioning* services or ecosystem goods [7–22], neglecting to account for *regulating*, *supporting* and *cultural* services. For example, the largest LCI database worldwide, i.e. Ecoinvent [23], accounts for hundreds of ecosystem goods (e.g. mostly fossil fuels and minerals, and few elementary flows of freshwater, wood and renewable energy), but does not model any link to other ecosystem services such as water and climate regulation, nutrient cycles, pests and diseases, pollination, soil formation, photosynthesis, etc. These EGSs are crucial for the production e.g. of agri-food and forestry products, but they are ultimately not inventoried by using physical metrics in LCI.

Beyond LCA, other environmental accounting tools have been developed to assess the value of ecosystems. For example, the Emergy analysis method developed by H.T. Odum [24, 25] is considered one of the most comprehensive common denominators for biophysical evaluations of EGSs [26–31]. Indeed, emergy measures the human and environmental work previously required to generate products and services [25]. In other words, Emergy encompasses the entire system boundaries of the Earth, because it accounts for the ultimate independent sources of energy that feed all the natural cycles: sun, tides and crustal heat. Emergy is thus able to approximate the environmental work necessary to replace what is used, presenting a unified measure of resource consumption, i.e. the solar energy directly and indirectly driving all geobiosphere processes [32]. The unit emergy value (UEV) represents the conversion factor to calculate the Emergy content of any kind of good or service. For LCA purposes, interest is addressed toward the use of UEVs as CFs for LCIA based on Emergy [10, 32, 33]. In such a way, the use of Emergy principles could benefit and expand the calculation of EGSs in LCA [34, 35].

The aim of this work is to outline possible research paths in the analysis of the

contribution of EGSs to life cycle products by using the Emergy method. Accordingly, the rest of the paper is organized as follows: the Emergy accounting procedure is briefly illustrated and a state-of-the-art is then given with regard to the main attempts performed to value EGSs with an Emergy-oriented approach. Afterwards, a library of UEVs for EGSs mid-point assessment is provided, where values are collected from the literature and their meaning investigated in accordance with the requirements of the most used LCI databases. Finally, conclusions are drawn according to the main limitations, advantages and possible follow-ups of the methodology.

## 2 Emergy concept and evaluation procedure

In its conventional definition, Emergy, spelled with an “m”, represents the of available energy used up in the entire chain production and incorporates the solar energy previously required to generate a product and/or to support a system and its level of organization [25]. Emergy is indeed the memory of the (solar) energy that has been used in the past or accumulated over time, or the memory of the geobiosphere Emergy provision (environmental work) related to economic systems via the use of natural resources [36,37]. Emergy stems from the qualitative and quantitative consideration that all different forms of energy can be hierarchized and measured with the common metric of the solar emjoule (seJ) [24,25]. To convert material and energy items into seJ, the method uses a conversion factor called *transformity* or unit emergy value (UEV), which is the Emergy required to make one unit of a given product or service [24,25] (see later in Sect. 3).

The calculation of UEVs is rooted in the “Baseline” concept [38,39]. This concept states that resource stocks and flows are co-products of the same global Emergy budget (i.e. baseline) that drives all geobiosphere processes (see Fig. 1). The Emergy baseline is the sum of solar radiation Emergy, tide Emergy, and geothermal heat Emergy. In order to assign an Emergy value (i.e. equivalents of joules of solar energy) to these three

different sources, a number of (linear) balance equations are initially applied [38,39]. As a result, the Emergy of 1 unit of tidal energy absorbed and of 1 unit of crustal heat is 72 400 and 20 300 times higher, respectively, than the emergy of 1 unit of solar energy absorbed [39]. This means that 72 400 and 20 300 joules of solar energy are assumed to make, respectively, 1 joule of tidal energy absorbed and 1 joule of energy from crustal heat sources. The total annual baseline is therefore composed of 24% of solar Emergy, 54% of tidal Emergy, and 22% of geothermal Emergy. As described in Section 3, the baseline is used to quantify the different EGSs with a hierarchical perspective (i.e. the larger the amount of the ecosystem good or service, the lower the UEV). Since the UEVs are applied afterwards to convert the energy and material inputs to human products and systems into seJ, other UEVs are then quantified in cascade (i.e. input Emergy divided by the output) and can be used for further applications.

## 3 Emergy and ecosystem services

Ecosystems are supported by continuous flows of Emergy, which ensure their functioning and dynamics and the provision of goods and services to sustain humans and other species. Emergy is thus considered to have “donor” features, because it expresses the role of a free ecological contributor to global and local equilibria in the geobiosphere. The anthropic technosphere is a primary receiver of, and strictly depends on those “not priced” Emergy inputs from the ecosystems. However, the role of humans in the geobiosphere is strongly utilitarian and not counterpart to that of other species. As a result, ecosystem goods and services are acknowledged only for the benefit they can give to technology development, which means the value of natural resources is weighted on their unique quality of being competitive for human purposes (e.g. quantity of Energy or Exergy that can be used or extracted). Therefore, the willingness to pay for the ecological contributions is based only on the intrinsic ability of the ecosystem services to provide benefits for humans, while the remaining but essential rucksack

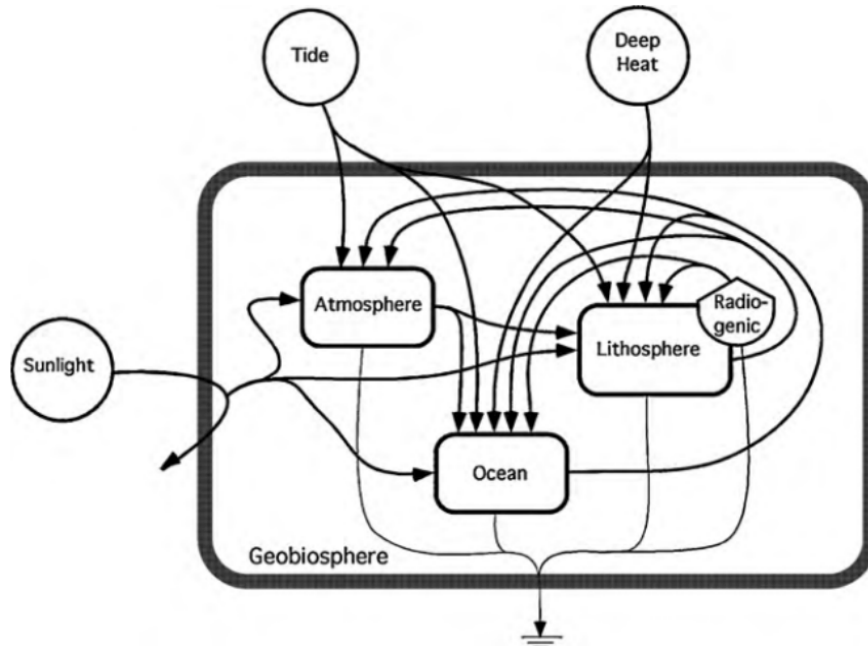


Fig. 1. Hierarchical web of components in the Earth’s geobiosphere, connected by flows of available energy independently supplied by sunlight, deep heat and tide sources (source: [39]).

of complexity, information, ability to support other species and to regulate natural equilibria, in other words “the natural effort”, is usually neglected. Emergy attempts to overcome this lack.

Many studies have suggested Emergy as a promising tool to support environmental management actions and public planning policies, because of its ability to characterize the dynamics of territorial systems e.g. [40,41]. According to Odum and Odum [30], Emergy-based valuation would avoid neoclassical approaches that “would not capture real contributions of ecosystems and could delay the organization of a sustainable pattern of environment and people”. Conventional approaches related to ecological economics, such as willingness-to-pay based on the contingent valuation method, usually capture the value of ecosystem entities narrowly and anthropocentrically, while in contrast, Emergy tries to estimate their *ecocentric* value [29, 42]. Several authors have attempted to estimate this value from a physical perspective. During the past decade, Ulgiati, Brown and co-authors tried to determine the natural capital required for the development of human systems [28, 43, 44], and also to estimate

the ecosystem services necessary to support waste dilution and abatement [45]. Watanabe and Ortega have recently quantified several UEVs for ecosystem services related to water, carbon and nitrogen cycles on the global scale [29]. Other scholars actively contributed to give insights on how to assess the EGSs’ influence on a high diversity of natural and human-driven systems from a biophysical Emergy perspective, such as wastewater treatment performances [46], estuarine ecosystem networks [47], river diversions [48], and peri-urban systems [49]. For this latter, in particular, the authors provided a comprehensive land cover change analysis to assess the decrease in EGSs provision on a very local scale, providing methodological findings in terms of effective spatial plans for controlling urban growth while protecting ecosystem functions. A study of linked relevance to this context is that performed by Montesino, who tried to explicitly account for the Emergy of several EGSs (i.e. biomass production, pollination, pest control, erosion control, nitrogen cycle, water cycle, carbon sequestration, biodiversity, aesthetic services) required in Danish agricultural systems of energy crops [50], providing a sort of “mid-point” assessment.

Emergy analysis is also able to integrate, in seJ, all flows within a system of coupled economic and environmental work, facilitating direct comparisons between natural and human-made capital [25, 51, 52]. Because goods and services are exchanged in the technosphere by means of money, Emergy adopts an artificial method to convert the seJ into the regional currency in order to estimate the apparent cost of ecological contributions to human processes. Accordingly, the Emergy-to-money Ratio (EmR, in seJ/\$ or other currency) has been implemented, which is the ratio of Emergy use in a country or a region to its GDP. The EmR estimates the amount of Emergy that, on average, is necessary to obtain one unit of money produced in a region, and therefore it represents the *environmental cost* associated with the economic wealth of that region. The output Emergy can be divided by the average EmR of an economic system to translate the seJ into Emdollars (Em\$). Therefore, the Em\$ becomes a metric familiar to the market language and makes Emergy comparable with cost-benefit and economic analyses [25–27, 52].

Several Emergy studies have been performed to evaluate the cost of EGSs in terms of Em\$. For example, Tilley and Swank [53] investigated in depth the benefits provided by the wine spring creek (WSC) forested watershed (southern Appalachian Mountains of North Carolina, USA) for the local economy, environment and society, while Cohen et al. performed an in-depth investigation of the Emergy environmental and economic costs of soil erosion losses on different scales in Kenya [51]. Odum et al. [54] quantified the net public benefit of reforestation alternatives in Puerto Rico, finding that natural wealth accumulated to a level 15–25 times the money invested in the 10–20 yrs required for canopy closure. Other authors, instead, studied dam construction projects, which often induce significant ecological and environmental change, to assess how the functional benefits of water supply, flood control and power production compare with ecosystem and agricultural losses [55, 56].

More recently, Pulselli et al. [27] compared the Emergy outcomes of EGSs analysis with those resulting from the application of

conventional techniques of ecosystem services valuation (ESV) as provided in reference [3]. They found that, globally, Nature contributes to humans not only more (as in Ref. [3]), but in a more efficient way, than all the world's economic infrastructures [27]. So far, Emergy would not be an alternative method to ESV techniques, but rather a complementary and systemic approach to highlight the mechanisms of service production by different systems [27]. Indeed, current economic ESV methods consist of "internalizing externalities" by devising approaches to value non-market-traded goods and services [57]. Odum and Odum [30] suggest that we need to "externalize the internalities" by using solar energy as the basis for valuing goods and services provided by our natural and human environments; therefore, Emergy could potentially fill a significant gap in adequately valuing EGSs and managing natural environments better. The Em\$ might be a useful metric to assess the end-point framework in the use of EGSs. However, its meaning and effectiveness for environmental policies must be better clarified and more widely accepted.

#### 4 Emergy-based mid-point LCIA factors

As mentioned before, Emergy is able to distinguish and compare the work done by humans with the work done by Nature. Both of them can be accounted for in joules of equivalent solar energy, and portions of renewability and non-renewability depicted. As a result, a large number of UEVs for natural and technological products are made available. In the former case, the effort of Nature in generating the ecosystem good or service is quantified per unit of product (i.e. biosphere resource UEVs), while in the latter case, the amount of natural investment is added to the amount of human investment to produce the final market good or service product (i.e. technosphere product UEVs).

To obtain technosphere product UEVs with a LCA perspective, the biosphere resource UEVs can be retrieved and used as CFs, thus allowing an Emergy-based LCIA [10]. The resource UEVs are usually representative of large-scale natural

processes or global cycles. An established procedure to set for the flows (i.e. inputs of elements, raw materials, natural energy carriers, and outputs) to be included in the UEV inventory does not exist, due to the large complexity of the natural systems: modeling for ecosystem dynamics is inherently very complex and subject to high degrees of uncertainty.

The approach of accounting for a UEV or a group of UEVs of EGSs is based on variable paths and assumptions. The current accepted and common feature remains the use of the “baseline”. Since solar energy is the primary source that feeds all processes and cycles on the Earth, inputs to a process can be normalized to a common unit, i.e. the seJ, which is the common (physical) numeraire to account for the value of EGSs in Emergy. Therefore, to assess the ecosystem contribution to a life cycle production system, all inputs of EGSs can be converted into Emergy flows via

$$UEV_i = CF_i = \frac{S}{F_i} \quad (1)$$

and

$$F_i = \frac{Q_i}{\Delta T_i} \quad (2)$$

where  $UEV_i$  is the Unit Emergy Value of the  $i$ th ecosystem good or service flow (in seJ/g, seJ/m<sup>3</sup>, seJ/J, etc.), which can be adopted as the characterization factor ( $CF_i$ ) for mid-point Emergy-based LCIA;  $S$  is the Emergy baseline (=15.2E + 24 seJ/yr; see [38, 39] for the comprehensive mathematical derivation of this number);  $F_i$  is the annual provision (or amount) of the  $i$ th ecosystem good or service flow on the global scale (in g/yr, m<sup>3</sup>/yr, J/yr, etc.);  $Q_i$  is the estimated storage (or global capacity) of the  $i$ th ecosystem good or service (in g, m<sup>3</sup>, J, etc., in particular with regard to *provisioning* services or resources); and  $\Delta T$  is the turnover time or estimated regeneration rate, in yrs (accordingly, a renewable resource is assumed when  $\Delta T = 1$  yr). In this connection, the notion of time is usually referred relatively to the state of the geological or biological (estimated) time of formation, which corresponds to the turnover time of the resource as being potentially regenerated from scratch (e.g. 5.19E + 08 yrs in the case of granitic rock, [25]). The variables expressed

in equations (1) and (2), in particular with regard to the amount of stock of the resources (e.g. groundwater, crude oil or iron reserves on the global scale), can be retrieved from the extant literature on global geobiosphere processes and Earth cycles (see in [25, 28, 39] for a more in-depth overview of the available sources). Therefore, their accuracy and representativeness depends on the quality of estimations included in those sources of biogeophysical and natural resource datasets.

In the Emergy literature, a large number of UEVs of natural resources is available [10], such as for water flows and storage [58], renewable energy resources such as wind or geothermal heat, biomass resources, different kinds of minerals and fossil fuels [25, 38, 59]. A summary of resource flow UEVs has been provided by Brown and Cohen [60]. Recently, UEVs were calculated for a large number of metal ore resources [61]; besides this, the calculation for fossil resources of gas, crude oil and coal was also upgraded [62]. These are all ecosystem goods that can be regarded as *provisioning* services and further used for LCIA purposes. Accordingly, the most used LCI databases such as Ecoinvent [23], or the recent International European reference life cycle database (ELCD) [63], usually include a large number of resource extraction elementary flows, both of biotic and abiotic nature. In Table 1, a simplified illustration of these two LCI databases with regard to *provisioning* services (i.e. elementary flows of resource) is reported, with a comparison in terms of number of ecosystem goods accounted for and levels of classification (i.e. category detail). Both the datasets include a large number of flows (i.e. #287 and #165 in the Ecoinvent v2.2 and ELCD, respectively), but the focus is mainly on non-renewable resources such as minerals, metals and fossil fuels. The evaluation of biotic flows as well as water and renewable energy is quite scarce in both cases. Moreover, while Ecoinvent accounts for many flows of LU (more than 130), the ELCD explicitly distinguishes between non-renewable and renewable resources.

In Table 2, an extensive library of UEVs of EGSs is provided, which might be used as mid-point characterization factors for

Table 1. Levels of classification of resource elementary flows in ELCD [63] and Ecoinvent [23].

Nr. Flows ELCD:	Level 1	Level 2	Level 3	Unit
139	Non-renewable resources	from ground		
134				
76			element*, e.g. "arsenic"	kg
7			energy, e.g. "crude oil"	MJ
51			material, e.g. "gravel"	kg
5		from water		
4			element, e.g. "bromine"	kg
1			material, e.g. "sodium chloride"	kg
26	Renewable resources			
12		from air		
8			element, e.g. "argon"	kg
2			energy, e.g. "primary energy from solar energy"	MJ
2			material, e.g. "carbon dioxide"	kg
3		from biosphere		
2			energy, e.g. "biomass"	MJ
1			material, e.g. "moisture (biomass)"	kg
3		from ground		
1			energy, e.g. "primary energy from geothermics"	MJ
2			material, e.g. "soft wood (dry matter)"	kg
8		from water		
2			energy, e.g. "primary energy from waves"	MJ
6			material, e.g. "river water"	kg
<i>Ecoinvent:</i>				
7		(assumed here)		
3		biotic		
4			energy and fuels**, e.g. "energy, gross calorific value, in biomass"	MJ
5			materials, e.g. "wood, hard, standing"	m <sup>3</sup>
3		in air		
2			elements and materials, e.g. "krypton", "carbon dioxide, in air"	kg
130			energy, e.g. "energy, solar, converted"	MJ
120		in ground		
7			elements and materials, e.g. "cobalt, in ground", "gravel, in ground"	kg
3			energy and fuels***, e.g. "coal, brown, in ground", "uranium, in ground"	kg
13		in water	occupied land, e.g. "volume occupied, underground deposit"	m <sup>3</sup>
3			elements, e.g. "iodine, 0.03% in water"	kg
1			energy, e.g. "energy, potential (in hydropower reservoir), converted"	MJ
8			water flow, e.g. "water, river", "water, unspecified natural origin"	m <sup>3</sup>
1			occupied land, e.g. "Volume occupied, reservoir"	m <sup>3</sup> y
132		land		
42			occupied land, e.g. "occupation, arable"	m <sup>2</sup> y
45			transformed land to, e.g. "Transformation, to forest, extensive"	m <sup>2</sup>
45			transformed land from, e.g. "Transformation, from mineral extraction site"	m <sup>2</sup>

\* "polonium" element is accounted for in kBq (unit of frequency).

\*\* "peat, in ground" is an energetic (fuel) biotic flow accounted for in kg.

\*\*\* "energy, geothermal" is accounted for in MJ and two flows of natural gas ("gas, mine, off-gas, process, coal mining" and "gas, natural, in ground") in N m<sup>3</sup>.

Table 2. Library of selected UEVs for mid-point impact characterization of EGs in LCIA; †MEA = Millennium Ecosystem Assessment [1].

†MEA Service category	Sub-category	(Intermediate) Ecosystem goods and services	Unit	Amount	Spatial reference	Source
Provisioning	Minerals and mineral aggregates	Oceanic basalt	se/g	2.40E+08	average, global	[38]
Provisioning	Minerals and mineral aggregates	Continental sediment	se/g	2.05E+09	average, global	[38]
Provisioning	Minerals and mineral aggregates	Shale	se/g	3.87E+09	average, global	[38]
Provisioning	Minerals and mineral aggregates	Sandstone	se/g	8.12E+09	average, global	[38]
Provisioning	Minerals and mineral aggregates	Limestone	se/g	9.02E+09	average, global	[38]
Provisioning	Minerals and mineral aggregates	Evaporites	se/g	1.62E+11	average, global	[38]
Provisioning	Minerals and mineral aggregates	Granitic rock	se/g	8.04E+08	average, global	[25]
Provisioning	Minerals and mineral aggregates	Metamorphic rock	se/g	2.33E+09	average, global	[25]
Provisioning	Minerals and mineral aggregates	Soil clay	se/g	3.25E+09	average, global	[25]
Provisioning	Minerals and mineral aggregates	Volcanic sediment	se/g	7.31E+09	average, global	[25]
Provisioning	Minerals and mineral aggregates	Salt	se/g	1.46E+08	average, global	[64]
Provisioning	Water resources	Rivers and streams	se/g	5.07E+05	average, global	[58]
Provisioning	Water resources	Freshwater lakes	se/g	3.65E+05	average, global	[58]
Provisioning	Water resources	Global groundwater recharge	se/g	1.81E+06	average, global	[58]
Provisioning	Metal ores	Aluminum	se/g	5.35E+09	average, global	[61]
Provisioning	Metal ores	Antimony	se/g	4.06E+12	average, global	[61]
Provisioning	Metal ores	Cadmium	se/g	3.25E+13	average, global	[61]
Provisioning	Metal ores	Chromium	se/g	1.49E+11	average, global	[61]
Provisioning	Metal ores	Cobalt	se/g	1.30E+11	average, global	[61]
Provisioning	Metal ores	Copper	se/g	9.47E+10	average, global	[61]
Provisioning	Metal ores	Gold	se/g	4.87E+11	average, global	[61]
Provisioning	Metal ores	Iron	se/g	1.16E+10	average, global	[61]
Provisioning	Metal ores	Lead	se/g	4.64E+11	average, global	[61]
Provisioning	Metal ores	Manganese	se/g	3.42E+11	average, global	[61]
Provisioning	Metal ores	Mercury	se/g	4.01E+13	average, global	[61]
Provisioning	Metal ores	Molybdenum	se/g	6.77E+11	average, global	[61]
Provisioning	Metal ores	Nickel	se/g	1.93E+11	average, global	[61]
Provisioning	Metal ores	Palladium	se/g	1.19E+11	average, global	[61]
Provisioning	Metal ores	Platinum	se/g	3.57E+11	average, global	[61]
Provisioning	Metal ores	Silver	se/g	4.33E+11	average, global	[61]
Provisioning	Metal ores	Tantalum	se/g	1.62E+11	average, global	[61]
Provisioning	Metal ores	Tin	se/g	1.62E+12	average, global	[61]
Provisioning	Metal ores	Titanium	se/g	6.27E+10	average, global	[61]
Provisioning	Metal ores	Uranium	se/g	1.56E+11	average, global	[61]
Provisioning	Metal ores	Zinc	se/g	6.96E+10	average, global	[61]
Provisioning	Metal ores	Cerium	se/g	1.10E+10	average, global	[61]
Provisioning	Metal ores	Gallium	se/g	1.71E+10	average, global	[61]
Provisioning	Metal ores	Indium	se/g	3.90E+11	average, global	[61]
Provisioning	Metal ores	Lithium	se/g	8.93E+11	average, global	[61]
Provisioning	Metal ores	Rhenium	se/g	8.63E+12	average, global	[61]
Provisioning	Metal ores	Rhodium	se/g	1.16E+12	average, global	[61]
Provisioning	Metal ores	Tellurium	se/g	4.87E+13	average, global	[61]
Provisioning	Metal ores	Zirconium	se/g	3.07E+10	average, global	[61]
Provisioning	Fossil fuels	Hard coal	se/J	9.71E+04	weighted mean, global	[62]

Table 2. Continued.

MEAs Service category	Sub-category	(Intermediate) Ecosystem goods and services	Unit	Amount	Spatial reference	Source
Provisioning	Fossil fuels	Soft coal	se//	6.63E+04	weighted mean, global	[62]
Provisioning	Fossil fuels	Crude oil	se//	1.48E+05	weighted mean, global	[62]
Provisioning	Fossil fuels	Natural gas	se//	1.70E+05	weighted mean, global	[62]
Provisioning	Genetic resources	DNA in leaves	se//	1.15E+07	average, forest scale	[25]
Provisioning	Genetic resources	DNA in seeds	se//	1.82E+09	average, forest scale	[25]
Provisioning	Genetic resources	DNA in species	se//	1.15E+12	average, forest scale	[25]
Provisioning	Genetic resources	Generate a new species	se//	7.68E+15	average, forest scale	[25]
Provisioning	Genetic resources	Generate global biodiversity	se//species	2.02E+25	average, global	[25]
Provisioning	Biomass resources	Herbivores	se//	1.22E+05	average, global	[28]
Provisioning	Biomass resources	Carnivores	se//	3.93E+06	average, global	[28]
Provisioning	Biomass resources	Top carnivores	se//	3.90E+07	average, global	[28]
Provisioning	Biomass resources	Phytoplankton	se//	1.77E+04	Alaska, local to regional	[65]
Provisioning	Biomass resources	Zooplankton	se//	1.61E+05	Alaska, local to regional	[65]
Provisioning	Biomass resources	Small nekton (molluskans, arthropods, small fish)	se//	1.77E+06	Alaska, local to regional	[65]
Provisioning	Biomass resources	Small nekton predators (fish)	se//	1.57E+07	Alaska, local to regional	[65]
Provisioning	Biomass resources	Mammals (seal, porpoise, belukha whale, etc.)	se//	6.16E+07	Alaska, local to regional	[65]
Provisioning	Biomass resources	Apex predators (killer whale)	se//	2.74E+08	Alaska, local to regional	[65]
Regulating	Water cycle	Evapotranspiration	se//g	2.34E+05	average, global	[29]
Regulating	Water cycle	Surface runoff	se//g	4.61E+05	average, global	[29]
Regulating	Water cycle	Water infiltration	se//m <sup>2</sup>	3.03E+11	Taipei peri-urban areas, local*	[49]
Regulating	Water cycle	Groundwater discharge to surface waters	se//m <sup>2</sup>	2.56E+11	Taipei peri-urban areas, local*	[49]
Regulating	Carbon cycle	Carbon sequestration, energy crop	se//g	1.14E+09	Denmark, local to regional	[50]
Regulating	Carbon cycle	CO <sub>2</sub> sequestration	se//g C	1.22E+08	average, global	[29]
Regulating	Carbon cycle	Runoff (org. and inorg. compounds)	se//g C	1.90E+10	average, global	[29]
Regulating	Nitrogen cycle	Runoff (org. and inorg. compounds)	se//g N	5.24E+11	average, global	[29]
Regulating	Energy resources	Surface wind	se//	2.41E+03	average, global	[25]
Regulating	Energy resources	Physical stream energy	se//	4.48E+04	average, global	[25]
Regulating	Energy resources	Global latent heat	se//	1.21E+24	average, global	[25]
Regulating	Energy resources	Global wind circulation	se//	6.19E+21	average, global	[25]
Regulating	Energy resources	Hurricane	se//	5.86E+20	average, global	[25]
Regulating	Energy resources	Global rain on land	se//g	1.05E+20	average, global	[25]
Regulating	Energy resources	Global rain on land (chemical potential)	se//g	4.98E+20	average, global	[25]
Regulating	Energy resources	Average river flow	se//g	3.80E+19	average, global	[25]
Regulating	Energy resources	Average river geopotential	se//	3.26E+20	average, global	[25]
Regulating	Energy resources	Average river chem. potential	se//	1.88E+20	average, global	[25]
Regulating	Energy resources	Average waves at the shore	se//	2.98E+20	average, global	[25]
Regulating	Energy resources	Average ocean current	se//	8.26E+17	average, global	[25]
Regulating	Energy resources	Kinetic energy of spring flow	se//	6.88E+03	average, global	[28]
Regulating	Other	Pollination, energy crop	se//	3.45E+10	Denmark, local to regional	[50]
Regulating	Other	Pest control, energy crop	se//	8.52E+06	Denmark, local to regional	[50]
Regulating	Soil	Erosion control, energy crop	se//	1.80E+06	Denmark, local to regional	[50]
Regulating	Biomass resources	Detritus	se//	6.34E+03	average, global	[28]
Supporting	Water cycle	Precipitation	se//g	1.45E+05	average, global	[29]
Supporting	Water cycle	Groundwater flow	se//g	4.00E+06	average, global	[29]
Supporting	Water cycle	Aquifer recharge	se//g	4.75E+06	average, global	[29]
Supporting	Water cycle	Water cycle, energy crop	se//g	1.87E+06	Denmark, local to regional	[50]

Table 2. Continued.

+MEA Service category	Sub-category	(Intermediate) Ecosystem goods and services	Unit	Amount	Spatial reference	Source
Supporting	Carbon cycle	Emission of CO <sub>2</sub>	seJ/g C	1.27E+08	average, global	[29]
Supporting	Carbon cycle	Emission of CH <sub>4</sub>	seJ/g C	1.54E+10	average, global	[29]
Supporting	Nitrogen cycle	Nitrogen cycle	seJ/g	6.29E+13	Denmark, local to regional	[50]
Supporting	Nitrogen cycle	Biological N fixation	seJ/g N	7.60E+10	average, global	[29]
Supporting	Nitrogen cycle	Volatilization of NH <sub>3</sub>	seJ/g N	8.00E+10	average, global	[29]
Supporting	Nitrogen cycle	Wet/dry deposition	seJ/g N	9.50E+10	average, global	[29]
Supporting	Nitrogen cycle	Denitrification to N <sub>2</sub> O	seJ/g N	1.09E+11	average, global	[29]
Supporting	Soil	Litter fall, soil formation	seJ/m <sup>2</sup>	1.75E+09	Taipei peri-urban areas, local*	[49]
Supporting	Biomass resources	Gross plant production	seJ/J	1.56E+03	average, global	[28]
Supporting	Biomass resources	Net plant production	seJ/J	4.47E+03	average, global	[28]
Supporting	Biomass resources	NPP	seJ/m <sup>2</sup>	9.13E+10	Taipei peri-urban areas, local*	[49]
Cultural	Other	Cultural value, forest areas	seJ/m <sup>2</sup>	2.99E+11	Taipei peri-urban areas, local*	[49]
Cultural	Other	Cultural value, agricultural production areas	seJ/m <sup>2</sup>	1.19E+12	Taipei peri-urban areas, local*	[49]
Cultural	Other	Aesthetic value, energy crop	seJ/J	5.54E+02	Denmark, local to regional	[50]

\* Values are originally provided in absolute terms (seJ/yr); UEVs are therefore reported in seJ/m<sup>2</sup> for consistency with the list of Energy intensity factors.

Energy evaluation in LCIA. The UEVs are grouped into the four categories of *provisioning, supporting, regulating* and *cultural* services. Each UEV has been collected from the most recent Energy literature and re-set (when not already given as such) on the latest quantified planetary baseline (=15.2E + 24 seJ/yr, [39]). This library represents a preliminary version, including a limited selection of UEVs (more than 100 elementary flows). Most of them can be regarded as provisioning services. Of course, other studies might be consulted in the future to update this list and to provide more specific UEVs. The time frame is not considered (there is not a reference year of calculation), while a rough reference condition for the spatial scale is provided (from global to local, when available).

### 5 Outlook on limitations and advantages

By definition, Energy aims to extensively account for natural processes, both at the global (e.g. atmospheric processes, land uplift, ocean current circulation) and regional scales (e.g. water runoff, soil erosion, surface wind, precipitations) [38, 52]. Despite this stated aim, the use of the baseline concept does not provide enough accuracy and detail on which processes are actually considered and how. Literature studies, rather than overtly rebut the baseline concept, provide a number of baseline values where components (i.e. sun, tide, geo) are weighted differently [25, 38, 39, 66]. Sciubba identified several uncertainty issues behind the Energy calculation of the three primary inputs to the geobiosphere, highlighting the potential ability of Exergy to compute the real “cost” of each component to the biosphere [67]. Since UEVs are calculated through a sort of pyramidal process starting from the baseline, it is not surprising to find large inconsistencies in Energy results, in particular when comparing systems that use different baselines at different times and on different spatial scales [66]. As a consequence, it is not necessarily obvious that Energy is the appropriate indicator to estimate the environmental work required to regenerate what has been consumed, because the future

temporal (and spatial) conditions for resource formation are likely to be very different from those of the past. Furthermore, UEV calculation is based on rather crude assumptions and results are therefore seldom reproducible [36,42,67] and cannot be validated a posteriori. In this respect, Emergy and LCA share the same limitations. However, due to its “memorization” (and non-conservative) character, Emergy is intuitively even more dependent on the degree of detail at which the system under study is described than LCA [34]. How to deal with the different uncertainty issues related to the calculation of UEVs is further discussed in [35], where the use of matrix inversion principles is recommended to calculate more consistent UEVs to avoid applying the baseline.

The effect of using the baseline also has further relevant impacts downstream in the EGS-UEV calculation. First, spatial and temporal variability is not included within the UEV models, which are assumed to be in steady-state conditions for a reference (undefined) year of EGS production and without specific downscaling properties to regional boundaries, i.e. the UEVs are representative of “average” global conditions. As a consequence, the Emergy value of EGSs that have a meaningful dependence on the regional scale, such as some provisioning (e.g. freshwater availability or biotic resources) or supporting (e.g. pollination) services, cannot be representative of the different local conditions around the globe. Second, the Emergy accounting procedure usually models the Emergy input associated with local resources (e.g. rain, sun) in such a manner that the Emergy input to a system does not fully contribute to the system development but instead a fraction is usually exported [68]. In this regard, we argue that only the equivalent (solar) energy that was actually needed to generate a given resource should be accounted for to give a more consistent evaluation of how much available energy is embodied in the UEV [35]. Finally, by using the baseline, the notion of “history” of resource formation (i.e. the accounting for solar inputs over geological time scales; [42]), as apparently stems from the definition of Emergy as *the available energy of one kind used up directly and indirectly to*

*generate resources and products* [25], seems to be completely missing. This is particularly true for most of the EGSs whose turnover time is greater than one year, those which are usually considered as non-renewable, i.e. minerals, metal ores, topsoil, groundwater, etc. Indeed, assigning with a top-down perspective a global production value (i.e. the baseline) to the annual flow of the resource (see Eq. (1)), means neither assessing how much available energy is memorized within the “life cycle” chain upstream of that ecosystem good or service, nor even being able to approximate the environmental work required to replace it in the future. The assumption that all the different biogeochemical flows, on the global scale, are co-products of the same annual contribution of solar Emergy (i.e. the baseline) makes the UEVs different solely because of the relative amounts of the flows on the globe. As a result, the lower the amount of the EGS flow (which of course depends on the ratio between stock and turnover time, see Eq. (2)) the higher the UEV, but without a clear link to the actual effort invested by Nature in generating that flow, which remains eventually unknown. Hence, it seems inappropriate hierarchizing UEVs of EGSs and considering them as indicators of “natural” efficiency.

On the other hand, the LCA method is less consistent than Emergy in the accounting for EGSs, where a limited number of EGSs is currently considered in LCIs [22] (compare Tab. 1 vs. Tab. 2). While Emergy attempts to evaluate the energy memory associated with information and with ecosystem services (e.g. *provisioning* and *regulating* services such as rain, tide and evapotranspiration, or *supporting* services such as soil formation and photosynthesis [22,27–30,51,52]), LCA does not generally account for those inputs because they are not specifically required/solicited by the economic systems, and are assumed to be freely available and not scarce. This approach indeed stems from the user-side perspective of LCA as compared with the donor-side perspective of Emergy. As a result, the combination of UEVs with existing LCI databases is not a trivial task, because of the complexity of the natural systems behind them and the missing inputs, which indeed are proven to

sustain human economies and should not be disregarded [35]. Research is ongoing in the LCA community to deal with this issue [7, 16–21]. It is expected that the system boundary of LCI will be enlarged in the near future with inclusion of a meaningful set of ecosystem services [69], where eventually the UEV library outlined in Table 2 might be harmonized.

## 6 Conclusions

As the “usefulness” of numerous, indirect EGSs remains unidentified, their contribution is likely to be minimized by using more traditional approaches based on solely monetary units (e.g. contingent valuation, willingness to pay). A relevant indicator for LCIA needs to accept scope enlargement and refining. Emergy accounts for the ecosystem contribution invested in order to obtain a product and therefore can potentially provide insightful information on the long-term sustainability of human processes [32]. The integration of Emergy into LCA might deliver a paradigm shift to the latter, by providing an assessment perspective larger than the common anthropocentric one, toward a Nature-oriented evaluation of natural resource use. Emergy appears as a complementary approach to LCA, because it goes beyond the accounting for natural resources by evaluating the environmental work needed for their formation. It provides a unique common metric of evaluation (i.e. the seJ), which enables one to put all EGSs on the same scale. However, Emergy has been strongly criticized due to its lack of overall consistency, which has hampered its acceptance and use during the past years [35, 36, 42, 67, 68, 70, 71]. It has been observed that the integration between Emergy and LCA is feasible but limited by a number of uncertainty elements and by an unclear definition of the resource UEV calculation [37].

Despite the fact that the use of the extensive perspective of Emergy seems crucial to evaluate in LCA the support provided by ecosystem functions to technological processes [32], there is a strong need to standardize the calculation procedure of EGSs in Emergy before including it in LCA, in

particular with regard to the *regulating* and *cultural services* categories [22]. Indeed, the Emergy content (or UEV) of EGSs does not apparently have a direct or tangible value for humans due to the not completely clear meaning of the “donor- or ecological-oriented” definition of Emergy. The concept of ecosystem services ultimately embodies a user-side perspective. The cultural services, in particular, can be perceived as even more mankind-centered because they are directly beneficial only for humans, while other EGSs such as water regulation or pollination, in turn, directly influence the well-being of non-human species, while only indirectly providing benefits to humans. Commonly, when comparing systems, it is indicated that “the higher the UEV, the lower the efficiency of the process but the higher the quality of the product, because larger environmental cost can be associated with it”. However, this might not be always the case and the value of Emergy results should not be generalized as such. A lower UEV means that a lower amount of natural inputs (e.g., rain) is bestowed by the geobiosphere to obtain the final EGS or the same amount of inputs is necessary to obtain more quantity of a natural resource. Accordingly, we cannot state whether this lower amount of natural inputs is also a marker of less environmental impact, because the amount of environmental work can neither be related to the notion of scarcity nor interpreted as an entity valuable per se to be protected. In the conventional interpretation, however, the UEV is considered a measure of the scale of energy convergence, whereby higher UEVs are commonly associated with higher “environmental impact” following a sort of precautionary principle.

Scientists from the Emergy community, for instance through interdisciplinary studies (e.g. ecological network analysis, resilience, ascendancy e.g. [72–75]), should insist on trying to clarify the rationale behind the UEV as an indicator, which despite the potential seems to be coarsely used. Research is ongoing to refine the UEVs for elementary flows of EGSs, to harmonize the calculation procedures with regard to the allocation principles, which are quite different in Emergy than in LCA models [34], and to

expand the scope of the LCI system boundaries [35]. The Emergy-based mid-point impact characterization approach illustrated in this paper can provide, in the end, useful insights on how to face these constraints and future challenges.

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