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Ecosystem services, sustainability and thermodynamic indicators

Sven Erik Jørgensen *,1

Copenhagen University, University Park 2, 2100 Copenhagen Ø, Denmark

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ABSTRACT

It is proposed to calculate the value of ecosystem services by the annual increase of work capacity or eco-exergy. The annual increase of biomass for various ecosystems is known. By multiplication of the biomass increase by the average content of information as Kullbach's measure of information, in the various ecosystems, the eco-exergy or total work capacity is obtained. An economic value can be found by multiplication of the cost of work, which is about 1 EURO-cent per MJ. A comparison of this value with the values found by Costanza et al. (1997) shows that the value based upon the total work capacity is much higher. The ratio between the two economic values have been found for the various ecosystems. It has been found that the ratio is lower the more an ecosystem by a wide range of application possibilities is utilized. The ecosystems have been divided in five classes according to the ratio and thereby in accordance to our utilization of the total work capacity of various ecosystems.

1. Introduction

How can we estimate the value of the ecosystem services? Costanza et al. (1997) have found the value by adding the costs of all the services that we utilize by ecosystems: purification of air and water, recycling, recreational services and natural resources such as timber, fish and drinking water. All activities require energy that can do work. Services by ecosystems mean activities offered to the user of ecosystems and they could therefore be measured by the work capacity. It means as the total amount of eco-exergy (work capacity) that an ecosystem offers. The sustainability of nature (ecosystems) can also be expressed by the work capacity, because:

(1) Sustainability in the Brundtland's sense means that the same level of ecosystem services must be maintained for the future generation.
(2) The amount of energy to be used to break down an ecosystem = the work capacity of the ecosystem (Svirezhev, 1998).

This idea to measure ecosystem services and thereby sustainability by eco-exergy or work capacity is pursued in this paper and the results are compared with Costanza et al.'s results. It is a newly proposed approach, which inevitably will lead to the recommendation to apply eco-exergy or work capacity calculations of ecosystems as informative holistic indicators.

2. How do we calculate the work capacity of ecosystems?

Exergy or work capacity expresses the energy that can do work. It can therefore be found as the gradient (=difference in potential) × an extensive descriptor, dependent on the energy form, for instance (Jørgensen et al., 2007):

- chemical work energy = $(\mu_1 - \mu_2)N$; or
- pressure work energy = $(p_1 - p_2)(-V)$;
- potential work energy = $(h_1 - h_2)mg$;
- electrical work energy = $(V_1 - V_2)Q$.

We can distinguish between technological exergy and eco-exergy: technological exergy uses the environment as reference state and is useful to find the first class energy (work) that a power plant can produce.

Eco-exergy uses as reference state the same ecosystem with the same temperature and pressure but at thermodynamic – chemical equilibrium; see Fig. 1.

For calculation of ecosystem services, we will of course use the work capacity of ecosystems or eco-exergy. As the reference system has the same temperature and pressure and magnetic and electrical work in negligible, only the chemical work energy contributes to the work capacity of ecosystems. It means, as the

* Tel.: +45 44480600; fax: +45 44480682.
E-mail address: sej@farma.ku.dk.
[1] http://www.ecologicalmodel.net.

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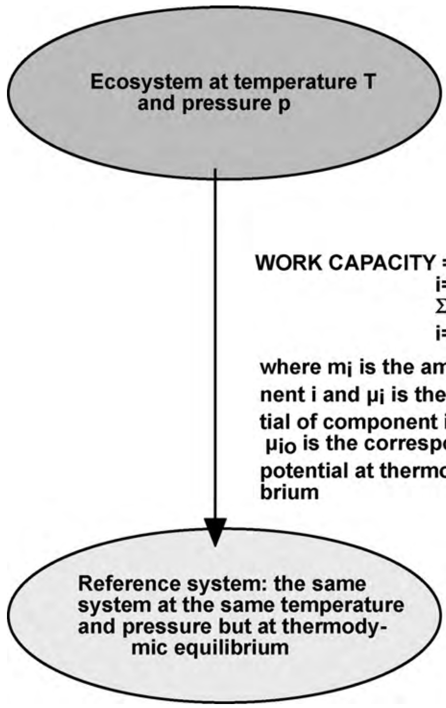

Fig. 1. The exergy content of the system is calculated with reference to the same ecosystem at the same temperature and pressure at thermodynamic equilibrium, it means as an inorganic soup with no life, biological structure, information, gradients and organic molecules.

chemical potential μ_i with good approximation is $\ln c_i$ that (Jørgensen et al., 2007):

$$\mathrm{Ex} = \sum_{i=0}^{i=n}(\mu_1 - \mu_2); \quad C_i = RT\sum_{i=0}^{i=n} C_i \ln \frac{C_i}{C_{i,o}}$$

Ex is the eco-exergy density. If we denote the total biomass concentration, A, we get:

$$A = \sum_{i=1}^{n} c_i; \quad p_i = \frac{c_i}{A}$$

$$E_x = ART\sum_{i=1}^{n} p_i \ln \frac{p_i}{p_{i,o}} + A \ln \frac{A}{A_o} = ARTK$$

where K is Kullbach's measure of information. It implies that the eco-exergy or work capacity density of an ecosystem with n different components (living organisms, detritus and inorganic matter – all components) can be found as (see also Jørgensen and Svirezhev, 2004; Jørgensen, 2002):

$$\text{eco-exergy} = \sum_{i=n}^{i=n} \beta_i \times c_i$$

where β is a weighting factor = $RT \ln c_i/c_{i,o}$ = $RT \ln p_i/p_{i,o}$, considering what the probability is to form the organism at thermodynamic equilibrium – $p_{i,o}$, i.e. how many amino acids in the right sequence is required to make up the organism, or how much information does an organism contain? β-Values found based on the genome size and by indirect methods can be seen in Table 1.

The value of the annual ecosystem services can be expressed by the annual increase of work capacity or eco-exergy. The annual growth of biomass – included growth of biomass, information and the ecological networks (see Jørgensen et al., 2000) – for the most common types of ecosystems can be found in general ecology textbooks or on internet. An average β-value for various ecosystems can be estimated based on the organisms that can be found generally in various types of ecosystems. Table 2 shows the annual biomass growth in MJ/m^2 using an average energy (exergy) content of biomass of 18.7 kJ/g, the applied average β-values and the work capacities in GJ/ha year found as the product of the biomass growth per m^2 and the β-value.

Table 1
β-Values = exergy content relatively to the exergy of detritus β-values = Eco-exergy content relatively to the eco-exergy of detritus (Jørgensen et al., 2005).

Early organisms	Plants	Animals	
Detritus	1.00		
Viroids	1.0004		
Virus		1.01	
Minimal cell		5.0	
Bacteria	8.5		
Archaea	13.8		
Protists (Algae)	20		
Yeast		17.8	
		33	Mesozoa, Placozoa
		39	Protozoa, amoebe
		43	Phasmida (stick insects)
Fungi, moulds	61		
		76	Nemertina
		91	Cnidaria (corals, sea anemones, jelly fish)
Rhodophyta	92		
		97	Gastroticha
Prolifera, sponges	98		
		109	Brachiopoda
		120	Plathyhalminthes (flatworms)
		133	Nematoda (round worms)
		133	Annelida (leeches)
		143	Gnathostomulida
Mustard weed	143		
		165	Kinorhyncha
Seedless vas-cula plants	158		
		163	Rotifera (wheel animals)
		164	Entoprocta
Moss		174	
		167	Insecta (beetles, flies, bees, wasps, bugs, ants)
		191	Coleodiea (sea squirt)
		221	Llpidoptera (butter flies)
		232	Crustaceans
		246	Chordata
Rice	275		
Gymosperms (incl. pinus)	314		
		310	Mollusca, bivalvia, gastropodea
		322	Mosquito
Flowering plants	393		
		499	Fish
		688	Amphibia
		833	Reptilia
		980	Aves (birds)
		2127	Mammalia
		2138	Monkeys
		2145	Anthropoid apes
		2173	Homo sapiens

Table 2
Annual work capacity increase by various ecosystems.

Ecosystem type	MJ/m^2 year As biomass	Beta-value (information factor)	GJ/ha year Eco-exergy
Desert	0.9	230	2070
Open sea	3.5	68	2380
Coastal zones	7.0	69	4830
Coral reefs, estuaries	80	120	960,000
Lakes, rivers	11	85	93,500
Coniferous forests	15.4	350	539,000
Deciduous forests	26.4	380	1.0 mill.
Temperate rainforests	39.6	380	1.5 mill.
Tropical rainforests	80	370	3.0 mill.
Tundra	2.6	280	7280
Croplands	20.0	210	420,000
Grassland	7.2	250	18,000
Wetlands	18	250	45,000

Table 3
Value of annual ecosystem services.

Ecosystem	kEURO/ha year (based on eco-exergy)	$/ha year according to Costanza et al. (1997)	Ratio
Desert	20.7	?	?
Open sea	23.8	252	94
Coastal zones	48.3	4052	12
Coral reefs, estuaries	960	14,460	66
Lakes, rivers	85	8500	10
Coniferous forests	739	969	763
Deciduous forests	1320	969	1362
Temperate rainforests	1580	?	?
Tropical rainforests	3200	2007	1595
Tundra	72.8	?	?
Croplands	400	92	4348
Grassland	175	232	754
Wetlands	450	14,785	30

The work capacity of various ecosystems can easily be compared with Costanza et al.'s (1997) values by using the energy costs:

- 1 MJ has the value of 1 EURO-cent or 1.4 $-cent.
- 1 GJ has therefore the value of 10 EURO or 14 $.

The values found on basis of the results in Table 2 are compared with Costanza et al.'s results in Table 3. The work capacity values give a much higher money value, which is not surprising, because the work capacities include all the possible services that the ecosystems offer – not only the services that we actually are utilizing. The ratio of the two sets of values is included in the last column of Table 3. We use evidently the ecosystems differently, which is able to explain the different ratios. The ecosystems can be divided into the five classes according to the different ratios, starting with the class which is utilized most by man for a series of services:

- A. Coastal zones, lakes, rivers: regulation, water supply, waste treatment, recreation, genetic resources, pollination, nutrient cycles, biological control, food production, refugia, transportation, raw materials, cultural; ratio about 10–20.
- B. Wetlands: regulation, water supply, waste treatment, recreation, raw material, genetic resources, pollination, nutrient cycles, biological control, refugia, cultural; ratio about 30.
- C. Open sea, estuaries, coral reef: only climate and gas regulation, very little waste treatment, much less recreation than A and B, raw material, genetic resources, pollination, nutrient cycles, (minor) biological control, (minor) refugia, raw materials, cultural; ratio about 60–90.
- D. Forests, croplands, grasslands and (deserts): mainly as raw materials, too little the genetic resources, pollination, nutrient cycles, biological control, (minor) refugia, cultural, recreation; ratio about >750.
- E. Cropland: croplands are only utilized to produce raw materials (mainly food); the ratio is therefore high, 4348.

3. Conclusions

The results can be summarized in the following conclusions:

- The total value of all services offered by the ecosystems may be estimated from the work capacity (eco-exergy) of the ecosystems.
- It is also a measure of the sustainability.
- We can divide the ecosystems in five classes according to how much we are able to utilize the entire spectrum of possible services.
- The sequence of our utilization of the ecosystem services is: lakes and rivers, coastal zones, wetlands, estuaries, open sea ecosystems, grasslands, forests and croplands.
- The sequence is understandable and explainable.

It is proposed in the paper to calculate the ecosystem services by use of eco-exergy or the work capacity of the ecosystems. The calculations can be used as measure for

– the entire spectrum of all the services that the ecosystems offer – not only the services that we actually utilize;
– the sustainability – at least indirectly.

It is therefore recommended to use the calculations of eco-exergy of ecosystems as a very informative holistic ecological indicators.

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