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## Valuating potential ecosystem services with a life-cycle oriented methodology

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The ecosystem services concept is a utilitarian and anthropocentric view of nature that can be defined roughly as “what humans obtain from ecosystems” (Haines-Young and Potschin, 2018). Numerous methods exist for valuating ecosystem services, notably contingent methods (e.g., willingness to pay, willingness to accept). An objectivised method, however, could better assess the level of each ecosystem service. Zhang et al. (2010 a,b) identified life-cycle-oriented methodologies that could value ecosystem services. Among them, we retained Life Cycle Assessment (LCA) (ISO, 2006) and Emergy Accounting (Odum, 2002). LCA, recognised worldwide, estimates potential environmental impacts due to resource consumption and pollutant emissions, while Emergy Accounting, a promising method, estimates cumulative emergy supply (environmental work) related to a product or service via the use of natural resources and social and manufactured inputs. We developed a methodology based on combining LCA and Emergy Accounting to value a bundle of ecosystem services of an anthropised ecosystem.

Our methodology is based on the four steps of LCA.

(i) *System boundary definition* consists of defining boundaries around the ecosystem of interest, the technosphere that manages it and the ecosphere that supports it. Within the system boundary, the ecosystem (i.e. biotic components, abiotic components, their interactions) is modelled and linked to the ecosphere and technosphere. A functional unit of the ecosystem is defined, such as to “occupy an area” (ha, km<sup>2</sup>) to supply a bundle of ecosystem services. A bundle of ecosystem services is then defined for the ecosystem. To do so, we used the Common International Classification of Ecosystem Services approach (Haines-Young and Potschin, 2018).

(ii) The *ecosystem flux inventory* consists mainly of quantifying the capture and emission of matter by the ecosystem and its components (e.g. organisms, water, soil), as well as the emergy value of each of these fluxes. The quantification must remain consistent with the modelling assumptions made during the first step.

(iii) *Potential ecosystem services valuation* has two steps. First, each flux is linked to an ecosystem service to aggregate fluxes into ecosystem services. Then, LCA indicators are used to value each ecosystem service. Midpoint indicators represent its potential biophysical value, such as kg CO<sub>2</sub> eq. captured, for the global regulation ecosystem service. Endpoint indicators represent its potential utilitarian value, such as the DALY it provides (meaning that it may extend human life). The emergy value of each flux is aggregated into its ecosystem service. Finally, each ecosystem service has two metrics: potential value (biophysical or utilitarian unit) and potential environmental work done to produce the service.

(iv) *Valuation interpretation* follows the classic LCA step. The two metrics of each ecosystem service are compared, as are the ecosystem services to each other. Sensitivity analysis can reveal synergies and trade-offs among ecosystem services for both metrics. Uncertainty analysis can show the accuracy of the methodology resulting from the assumptions made during the first three steps.

Our methodology will be applied and then validated using an anthropised ecosystem: a fish pond farm in France. The metrics will permit us to analyse multiple aspects of the concept of ecosystem services, estimating what the ecosystem supplies as ecosystem services (user-side) and, as a counterpart of this supply, its environmental work (donor-side) (Pulselli et al., 2011). This counterpart could be important for ecosystem management; indeed, it may be possible to maximise an ecosystem service while minimising the requisite work. It was difficult to take cultural ecosystem services into account individually and directly because of the environmental methodologies used. Nevertheless, the former can be evaluated as a group (cultural ecosystem services) and indirectly using Energy Accounting metrics (Huang et al., 2011). More generally, our methodology expands the Life Cycle Inventory (LCI) to include ecosphere inputs (*e.g.* sun, rain) and social inputs (*e.g.* human work, human services). It also improves Energy Accounting by combining it with LCA (Rugani and Benetto, 2012).

Our methodology is an initial step toward objective valuation of a bundle of ecosystem services. Despite the weak inclusion of cultural ecosystem services, it is able to consider the other categories of ecosystem services. The two metrics show different aspects of ecosystem services: what humans obtain from ecosystems and what the environment supplies as work for human well-being. The methodology improves the LCI by including previously-excluded inputs (ecosphere and social) and, more generally, improves Energy Accounting. Further development of the use of LCA indicators and the combination of LCA with Energy Accounting will enhance this methodology and ultimately the valuation of potential ecosystem services.

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