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Using Emergy to Value Ecosystem Goods and Services

Vivek Voora
Charles Thrift

February 2010

Prepared for Alberta Environment

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Executive summary

Emergy (not to be confused with energy) is the energy that is used directly and indirectly to make a product or provide a service. It can be thought of as an energy "memory," and its calculation is analogous to assessing past efforts that shaped our careers (family support, teacher efforts, books, tuition, meals, shelter and so on)(Campbell, 2008). Emergy practitioners claim that emergy is a more comprehensive and adequate way to value ecosystem goods and services (EGS), which are becoming increasingly rare due to the continued degradation of our world's natural environments. The International Institute for Sustainable Development (IISD) investigated the advantages and disadvantages of using the emergy approach to value EGS. The study consisted of conducting a brief literature review (21 primary articles), interviewing six relevant experts (three opponents and three proponents) and surveying current and former students (119 participants) in sustainable development and environmental fields.

The emergy approach uses nature's value system, which is based on flows of available energy that are appropriated and converted into forms that have the capacity to do more work. Energy flows alone are insufficient to value EGS, as they do not adequately convey the past work performed by the environment and the economy to produce a good or deliver a service. The emergy approach comprehensively and objectively values goods and services from the environment, society and the economy by expressing them in solar *emjoules*. Unlike the joule, which conveys the amount of available energy that can be used in the present, the emjoule conveys the energy used directly and indirectly in the past to produce something. Solar transformity coefficients, which represent the solar energy used in the past to make one joule of available energy in the present, are used to convert energy flows into emergy values in accordance with the following equation:

$$\boldsymbol{Emergy\ (sej) = Available\ Energy\ (J)\ \times Transformity\ (sej/J)}$$

Since all goods and services from the environment, society and the economy can be expressed in emergy units, they can be directly compared to assess the condition and sustainability of a system. The emergy approach provides policy- and decision-makers with a valuation system so that human and natural environments can be better managed.

The results from this study confirm that the emergy approach attempts to provide a more comprehensive EGS value. However, its ubiquitous appeal and methodology have been criticized by economists, ecologists and energy analysts. They describe its methodology as idiosyncratic, as they claim it does not follow the principles of additivity. In addition, emergy opponents believe that its conceptual complexity will limit its uptake within the realm of policy and decision-making. Emergy proponents maintain that the emergy approach respects the principles of additivity, as it only uses balanced energy and material flows, which are converted into emergy units to assess a system's sustainability. Despite its perceived conceptual and methodological complexity, the emergy approach

continues to be applied within academia and public agencies, such as the U.S. Environmental Protection Agency (U.S. EPA) and the U.S. Forest Service, to inform policy and decision-making (Brown & Campbell, 2007; Campbell & Ohrt, 2009).

The information gathered from the literature review, expert interviews and online survey all suggest that using biophysically grounded EGS-valuation methods is desirable. The use of the emergy approach in concert with economic instruments to value EGS could lead to a more complete assessment that reflects human preferences as well as the natural environment's evolutionary tendency toward energetic efficiencies.

We make the following recommendations for pursuing a broader investigation into and potential application of emergy and other energy-based EGS-valuation methods:

- Examine in greater detail the methods used to derive solar transformity coefficients and various conventions used to conduct an emergy analysis.
- Apply the emergy approach along with economic instruments to a study area where an EGS assessment is underway or has been completed.
- Organize a workshop among academic experts and policy-makers to discuss energy-based approaches (including emergy) and economically based approaches to valuing EGS.
- Expand this study to assess the potential of other energy-based EGS-valuation methods, such as net energy accounting, ecological footprint and net primary production.
- Examine the potential use of energy-based valuation methods (including the emergy approach) to assess supporting ecosystem services that cannot be adequately evaluated using economic approaches.
- Identify the decision-making metrics used by government departments to better understand how EGS-valuation information derived from economically and energetically based methods can be informative for these agencies and compatible with their needs.

In accordance with the saying "we can only manage what we measure," adequately valuing EGS requires a combination of biophysical and economic methods. The emergy approach provides a way to objectively and comprehensively assess goods and services from the environment, society and the economy using solar energy as a common unit of measure that allows for the assessment of a system's sustainability. Additional research on the emergy methodology is needed to determine whether it should be applied more widely to valuing EGS.

List of acronyms and abbreviations

%R	renewability
ED	emergy flow density
EER	emergy exchange ration
EGS	ecosystem goods and services
EI	emergy investment
EIR	emergy investment ratio
ELR	environmental loading ratio
EM	emergy matching
ESI	emergy sustainability indicator
ESR	emergy self-support ratio
EYR	emergy yield ratio
IISD	International Institute for Sustainable Development
Tr	solar transformity
U.S. EPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service

1.0 Introduction

Ecosystem goods and services (EGS) are the benefits we receive from our natural environments that are essential for our well-being. The Millennium Ecosystem Assessment reports that 60 per cent of ecosystems worldwide have been degraded or are being used in an unsustainable manner. Adequately valuing EGS can help decision-makers better manage natural environments so they can continue providing valuable services (see Appendix A).

Emergy (not to be confused with energy) is the "available solar energy used up directly and indirectly to make a service or product" (Odum, 1996, p. 8). This concept, which embodies 35 years of the late H.T. Odum's energy and ecology work, has been posited as a means to adequately value EGS, but has also been widely criticized (Brown & Ulgiati, 2004; Odum & Odum, 2000).

Current economic EGS-valuation methods consist of "internalizing externalities" by devising approaches to value non-market-traded goods and services. Odum & Odum (2000) 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. Also referred to as "embodied energy" or "energy memory," emergy could potentially fill a significant gap in adequately valuing EGS and better managing natural environments.

Alberta Environment is investigating different tools to value non-market-traded EGS to support decision- and policy-making and advance sustainable development planning. For this reason, they have requested that the International Institute for Sustainable Development (IISD) examine emergy's potential as a tool for valuing EGS. This study explores the advantages and disadvantages of using emergy measurements to value EGS and assess development alternatives. The research objectives for this study are the following:

- Explore the potential advantages and disadvantages of using emergy to value EGS.
- Examine emergy's potential to evaluate the costs and benefits of development alternatives.
- Explore with six experts the support and reservations associated with valuing EGS using emergy.
- Assess the uptake of emergy as a valuation technique by practitioners and students in environmental fields.

We used a short literature review, six semi-structured expert interviews and an online survey to fulfill the research objectives. The information gathered provided IISD with insights that enabled us to recommend future steps to allow Alberta Environment to move forward with their efforts to better value EGS. In general, IISD recommends further investigation of the emergy approach by either examining its methodology in more detail or by applying it within a study area that has been or is currently undergoing an ecosystem services assessment and expanding this study to examine additional biophysical EGS-valuation methods.

2.0 Literature review

We conducted a brief literature review to examine the potential of the emergy concept in valuing EGS. We gathered a collection of approximately 200 emergy documents by using an "emergy" keyword search in Science Direct (www.sciencedirect.com) and Google (www.google.ca). We compiled an annotated bibliography, and we filtered it down to a set of 21 documents (see Appendix B) for the literature review by focusing on EGS-related material and recently published documents (1999 and later, with the exception of H.T. Odum's 1996 book, *Environmental Accounting: Emergy and Environmental Decision Making*). We limited the number of documents reviewed to make the review manageable within the budget and time constraints of the project.

The literature review is organized into two sections: theoretical basis and applications. The theoretical basis provides some background information on the emergy concept, analysis methodology, and strengths and weaknesses. We then examine the emergy analysis applications used to assess the sustainability of regional developments, agricultural practices, and environmental preservation and restoration efforts.

2.1 Theoretical basis

Here we discuss and present the general concepts, methodologies, and strengths and weaknesses of the emergy approach. The emergy concept represents approximately 35 years of work in systems ecology, capturing H.T. Odum's lifetime of work. The methodology involved in carrying out an emergy analysis generally consists of three steps: (1) construct an energy systems diagram identifying the system's stocks and flows; (2) estimate emergy equivalencies of the stocks and flows using transformity coefficients, and (3) assess the system's sustainability using emergy indicators. We discuss the strengths and weaknesses of the emergy approach based on assessments provided in peer-reviewed academic literature.

2.1.1 *Background*

The emergy concept was derived from H.T. Odum's observation that various forms of energy have differing abilities to do work and hence different qualities. He then concluded that quality corrections or transformity values were required to adequately compare dissimilar forms of energy. This deduction led him to present the net energy concept to the U.S. House of Representatives subcommittee on energy and power of the committee on interstate and foreign commerce. He described the concept as follows: "The true value of energy to society is the net energy, which is that after the costs of getting and concentrating that energy are subtracted" (Brown & Ulgiati, 2004, p. 203). The U.S. Senate introduced and passed a bill in 1975 making net energy analysis mandatory for proposed alternative energy systems. This law, which was temporarily enforced, is now largely ignored (Brown & Ulgiati, 2004).

From 1975 to the present, emergy concepts and methodologies evolved significantly. The term "emergy" was coined by David Scienceman in 1983 by combining the words in "embodied energy," which Odum was then using to refer to the total solar energy required to make a product or supply a service (Brown & Ulgiati, 2004). Odum published Environmental Accounting: Emergy and Environmental Decision Making, a comprehensive account of the emergy concept and approach, in 1996. Box 1 captures some of the basic definitions and principles used in the emergy field.

Box 2.1 Common terms used in emergy field

Emergy. All the available energy that is used in the work of making a product, expressed using a common energy unit.

Emjoule. The unit of emergy, which has the dimensions of the energy previously used (gram-centimeter^2/sec^2)

Energy hierarchy. The convergence and transformation of energy of many small units into smaller **amounts of higher-level types of energy with greater ability to intersect with and control smaller units.**

Emdollar value. To calculate emdollars, you must first determine the national or regional ratio of emergy to money by dividing the total emergy output by the gross domestic product of the country or region. Once this emergy ratio (sej/$) is determined, you can then multiply it by the emergy value of a product or service to obtain a dollar value, or the *emdollar value* of the service or product being examined.

Net emergy. The emergy yield from a resource after all the emergy used to process it has been subtracted.

Emergy yield ratio. The ratio of the emergy yield to the emergy required for processing.

Solar transformity. Solar emergy per unit of energy, expressed in solar emjoules per joule (sej/J).

Transformity. A measure of the scale of energy convergence. In other words, the emergy of one type required to make a unit of energy of another type. For example, since three coal emjoules (cej) of coal and one cej of services are required to generate one joule (J) of electricity, the coal transformity of electricity is four coal emjoules per joule (4 cej/J).

Maximum power principle. An explanation for the design observed in self-organizing systems (energy transformations, hierarchical patterns, feedback controls, amplifier actions and so on). Designs prevail because they draw in more available energy and use it with more efficiency than alternatives.

(Sources: Odum, 1996; Odum, Brown & Brandt-Williams, 2000)

Researchers from a number of disciplines use this approach to value goods and services originating from natural and human systems. It has been applied to the examination of a number of different systems, including regional development, alternative energies, building efficiency, agricultural practices and natural environments (Giannetti, Barrella & Almeida, 2006; Lei, Wang & Ton, 2008; Meillaud, Gay & Brown, 2005; Menegaki, 2008; Odum & Odum, 2000; Pulselli, Pulselli & Rustici, 2008; Rydberg & Haden, 2006; Tilley & Swank, 2003).

Some researchers postulate that the emergy concept can assist in the valuation of EGS (Brown & Ugliati, 1999; Hau & Bakshi, 2004b; Odum & Odum, 2000; Ulgiati & Brown, 1998; 2009). "Emergy analysis presents an energetic basis for the quantification or valuation of ecosystem goods and services," say Hau and Bakshi (2004b, p. 215). Emergy offers a way to move beyond anthropocentric valuation methods by offering an eco-centric approach to valuing EGS. It does so by assigning a more comprehensive value to ecological and economic goods and services based on energy flows.

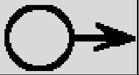
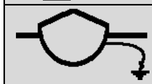
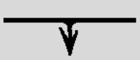
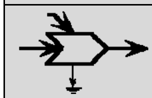
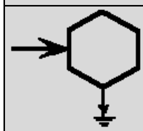
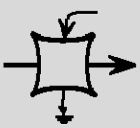
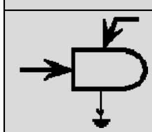
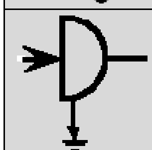
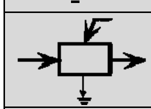
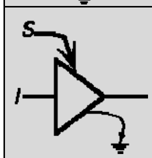
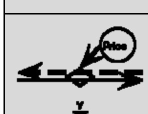
Although methodologies and applications have become more refined over the years, there is no consensus in the academic literature on using emergy outside the realm of systems thermodynamic analysis (Hammond, 2007; Herendeen, 2004). Nevertheless, emergy-related methodologies continue to be refined and their application broadened to assess human and natural systems (Almeida, Barrella & Giannetti, 2007; Giannantoni, 2003; 2006; Giannetti et al., 2006; Pulselli, Simoncini, Ridolfi & Bastianoni, 2008; Siche, Agostinho, Ortega & Romeiro, 2008).

2.1.2 *Methodology*

Emergy analysis is an environmental accounting method used to comprehensively assess a system's relationship with its human and natural surroundings by using similar units (Higgins, 2003). The general methodology used to conduct an emergy analysis consists of defining the system boundary and using energy systems diagrams to depict the system's features, inputs and outputs to be analyzed. The next step involves creating an emergy table summarizing the emergy values of the system's stocks and flows. The stocks and flows are converted from units of energy or mass to equivalent units of emergy by using transformity coefficients. The system's sustainability can then be evaluated using a number of emergy indicators.

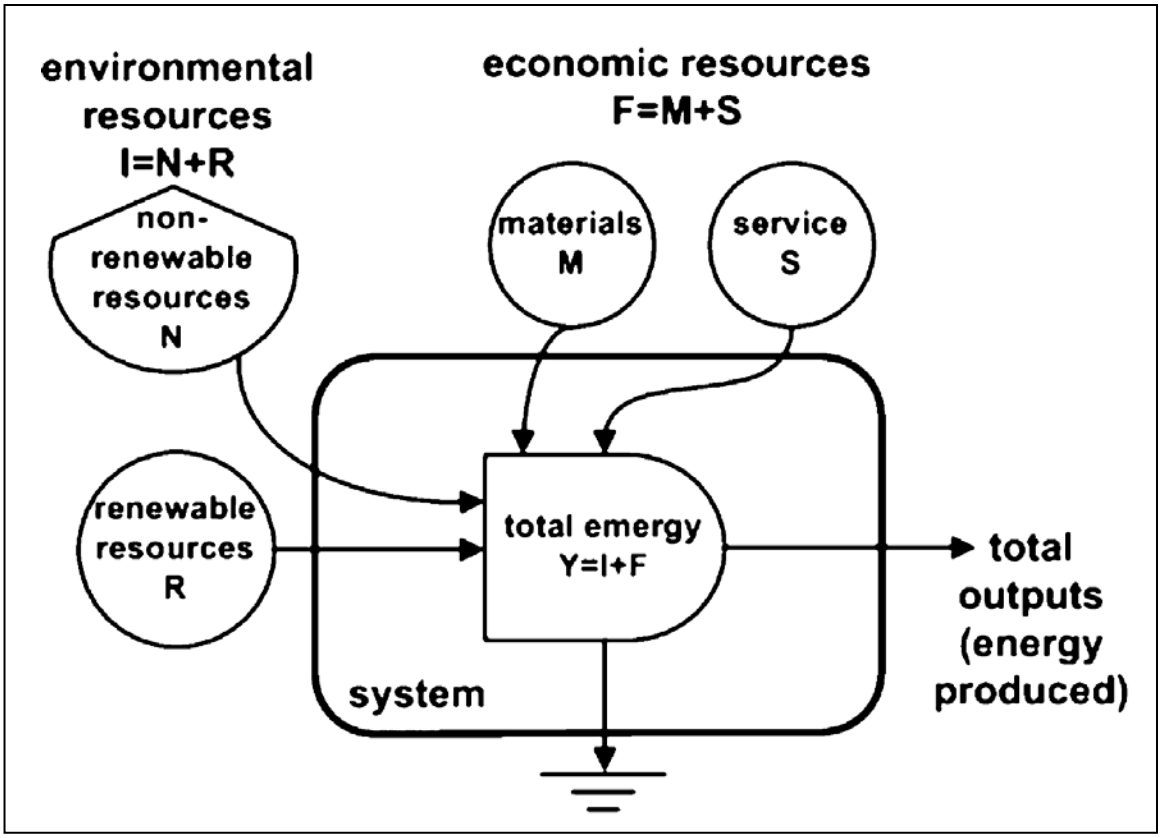
H.T. Odum derived the symbols used for compiling energy systems diagrams, which are similar to most symbols from other systems-modelling and programming languages. Table 2.1 shows the basic symbols used.

Table 2.1 Energy systems diagram symbols. Adapted from EmergySystems.Org (2003).

	Energy circuit: A pathway whose flow is proportional to the quantity in the storage or source upstream.
	***Source:*** An outside source of energy delivering forces according to a program controlled from outside; a forcing function.
	***Tank:*** A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.
	***Heat sink:*** The dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.
	***Interaction:*** An interactive intersection of two pathways required to produce a particular outflow, such as a product or service.
	***Consumer:*** A unit that transforms energy quality, stores it and feeds it back autocatalytically to improve inflow.
	***Switching action:*** A symbol that indicates one or more switching actions—which means that the process can be turned on or off. The controlled flows enter and leave from the sides, and the pathways (thresholds and other information) that control the switches are drawn on top. Examples of switching actions include earthquakes and flooding events.
	***Producer:*** These include units that collect and transform various inputs into a particular product. Examples of producers include plants and manufacturing processes.
	***Self-limiting energy receiver:*** A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.
	***Box:*** A miscellaneous symbol to use for whatever unit or function is labelled.
	***Constant-gain amplifier:*** A unit that delivers an output in proportion to the input, *I*, but is changed by a constant factor as long as the energy source, *S*, is sufficient.
	***Transaction:*** A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

These symbols are assembled to describe the functioning of a particular system, which usually consists of flows, tanks, producers, sources and heat sinks. Figure 2.1 shows the resources that flow from the environment and the economy to a producer yielding a product expressed as an energy flow.

Figure 2.1 **Emergy system diagram of a generic production system. Reprinted from Agostinho et al. (2008, p. 38).**



Once the system has been defined and sketched out and all its stocks and flows have been quantified, an emergy table can then be compiled. This is done by multiplying the system's quantified stocks and flows in units of mass, energy or money by the corresponding transformity value of those stocks and flows in accordance with the equation below. The four rules described in Box 2.2 are applied to assign emergy values to a system's stocks and flows.

$$\boldsymbol{Emergy\ (sej) = Available\ Energy\ (J)\ \times Transformity\ (sej/J)}$$

Box 2.2 **The four rules required to assign emergy to flows of energy.**

1. Assign all the source emergy of a process to the output(s) of the process.
2. For each by-product from a process, assign the total emergy to each pathway.
3. When a pathway splits, assign emergy to each leg of the split based on its percentage of the total energy flow in the pathway.
4. Do not count emergy twice within a system:
    a. Do not double count emergy in feedbacks.
    b. Do not add by-products, when reunited, to equal a sum.

(Source: Herendeen, 2004, p. 234)

To derive transformity values, one must capture all the resources and energy that went into making the product and express them in solar energy amounts. A range of transformities exist for a given product (see Table 2.2). The lower limit of the transformity range represents the most efficient approach to making the product. Odum (1996) maintains that transformities for a given product can be used to compare production efficiencies among systems.

Table 2.2 **General solar transformity values. Adapted from Odum (1996).**

Earth Processes and Products	Solar Transformity Value Ranges (Solar Emjoules/Joules)
Thermal Gradients, Wind	$1 - 10^{3}$
Water, Fuels, Electric Power	10^{3}-10^{6}
Animals, Protein, Food, Soil	10^{6}-10^{9}
Drugs, Chemicals	10^{9}-10^{12}
Information	10^{12}-10^{32}

Transformity values are derived for natural processes by first calculating the solar annual emergy flows for the geobiosphere, which is estimated to be 15.83 x 10^{24} solar emjoules per year, by evaluating solar insolation, deep heat and tidal energy (Odum et al., 2000). Transformities for various natural processes (surface wind, physical and chemical energy of rainfall, and waves absorbed on shores) can then be derived by dividing the geobiosphere's annual emergy flow by the processes' respective annual energy fluxes, estimated from meteorology, oceanography and earth science literature (see Appendix C). For an in-depth description of the methodologies used to derive the transformity coefficients for various natural and human processes, see chapters 3 and 4 in Odum's *Environmental Accounting: Emergy and Environmental Decision Making*. Although the transformity coefficients are derived using sound estimates, a number of refinements and adjustments could still be made in their calculation (Odum, 1996).

Once the system has been quantified in emergy units, it can then be analyzed by using a number of emergy indicators. For example, the emergy sustainability indicator (ESI) combines the emergy yield ratio (EYR) and the environmental loading ratio (ELR) to provide a sustainability indicator that captures the production capacity of the system and its burden on the natural environment (Brown & Ugliati, 1999). The ESI, when compared with other systems, could yield insights to help assess the sustainability of systems.

Table 2.3 Emergy analysis inputs and outputs and sustainability indicators. All descriptions from Chen et al. (2006), Pizzigallo et al., 2007, Ortega et al. (2005) and Agostinho et al. (2008).

Inputs and services	Expression	Meaning
Total emergy (Y)	$Y = I + F$	Emergy of total outputs
Nature's contribution (I)	$R + N$	Emergy of renewable and non-renewable resources
Renewable natural resources (R)		These could include rain, materials and services, nutrients from soil, minerals and air
Non-renewable natural resources (N)		These could include soil or biodiversity, but not people
Feedback from economy (F)	$F = M + S$	Total inputs originating from the economy and feeding back into the system
Materials (M): Renewable (Mr) and non-renewable (Mn) materials and energy	$M = Mr + Mn$	Renewable materials of natural origin. Non-renewable materials include minerals, chemicals, steels, fuel etc.
Services (S): Renewable (Sr) and non-renewable (Sn) services and externalities (Sa)	$S = Sr + Sn + Sa$	Renewable services include human labour supported by renewable sources, which can be local (Srl) and external (Sre). Non-renewable services include external services, taxes, insurance etc. Externalities include effluents, medical costs, job losses etc.

Table 2.3 continued

Inputs and services	Expression	Meaning
Emergy indicators		
Solar transformity (Tr)	$\frac{Y}{\sum Ep}$	Ratio of the output divided by the energy of the products
Renewability (%R)	$\frac{100x(R + Mr + Sr)}{Y}$	Ratio of renewable inputs divided by the total emergy of the system
Emergy yield ratio (EYR)	$\frac{Y}{Mn + Sn}$	Ratio of total emergy used divided by the emergy of non-renewable inputs from the economy
Emergy investment ratio (EIR)	$\frac{Mn + Sn}{R + Mr + Sr + N}$	Ratio of emergy of non-renewable economic inputs divided by the emergy of natural investments (natural inputs plus renewable inputs from the economy)
Environmental loading ratio (ELR)	$\frac{N + Mn + Sn}{R + Mr + Sr}$	Ratio of non-rewenwable emergy to renewable inputs.
Emergy exchange ratio (EER)	$\frac{Y}{\left[(\$)x\left(\frac{sej}{\$}\right)\right]}$	Ratio of emergy delivered by the producer to the economy divided by the emergy received from the sale of items produced
Emergy self-support ratio (ESR)	$\frac{R + N}{Y}$	Ratio of the emergy inputs to the total emergy
Emergy matching (EM)	$\frac{Subsystem}{Subsystem}$	Ratio that measures how well co-existent subsystems within an area balance one another in terms of their emergy values.
Emergy investment (EI)	$\frac{F}{(R + N)}$	Ratio between the emergy sources from the economy and free renewable sources
Environmental sustainability index (ESI)	$\frac{EYR}{ELR}$	Indicator of the sustainability of a system
Emergy flow density (ED)	$\frac{Y}{Area}$	Ratio of the emergy flow that is supporting a system divided by its area.
Social emergy indicators		
Labour services ratio (LSR)	$\frac{Sr}{S}$	This ratio represents human labour supported by renewable resources divided by the total value of services, including renewable and non-renewable services and externalities.
Labour empower ratio (LER)	$\frac{Sr}{Y}$	This ratio is defined as human labour supported by renewable resources divided by total emergy.
Labour work ratio (LWR)	$\frac{Srl}{S}$	The local human labour supported by renewable resources divided by the total value of services, including renewable and non-renewable services and externalities.
Externalities empower ratio (EER)	$\left(\frac{Sn}{Y}\right)$	The ratio is given by dividing the non-renewable services with the total emergy.

Detailed rules have been devised to ensure that the emergy assessments are conducted consistently. A number of conventions exist for drawing up energy-system diagrams, identifying flows to avoid double counting, compiling emergy tables and adequately assigning emergy values. For example, the items and flows are arranged in a diagram from left to right in order of their unit emergy transformities. For a detailed description of the emergy approach procedures, see Chapters 5 and 6 in Odum (1996).

2.1.3 *Strengths and weaknesses*

We briefly examine the strengths and weaknesses of the emergy by looking at some of its conceptual and methodological challenges. The main advantage of the emergy approach is that it enables one to comprehensively examine a system's sustainability by converting all flows and stocks from natural and economic sources into units of solar energy. However, this ubiquitous approach has led to criticism from economists, ecologists and engineers. Challenges related to perception and methodology are the greatest obstacles to achieving a broader acceptance and utilization of the emergy approach.

Emergy analysis comprehensively measures the sustainability of human and natural systems. Specifically, it can be used to account for estimating the work required to deliver ecosystem services, environmental flows of energy and storage of energy in the form of natural capital (Tilley, 2006). According to Hau and Bakshi (2004b) the emergy analysis offers a number advantages, as it:

- Provides a way to bridge economic and ecological systems.
- Provides an objective means by which to quantify and value non-market inputs into a system.
- Shares the rigour of thermodynamics and is scientifically sound.
- Provides a common unit that allows for a comparison of all resources.
- Provides a more holistic alternative to many existing methods of decision-making.

Emergy comprehensively measures value as it considers all contributions to the formation of a particular good or service. Odum has gone as far as suggesting that since emergy is a more complete measure of wealth, it could substitute for money (Hau & Bakshi, 2004b).

Although the emergy approach has a ubiquitous appeal, it has drawbacks, like many other environmental accounting methods (Hau & Bakshi, 2004b). Emergy critics generally complain that the method:

- Lacks formal links with related concepts in other disciplines.
- Lacks adequate details on the underlying methods.
- Is computationally and data intensive.
- Is based on sweeping generalizations that remain unproven.

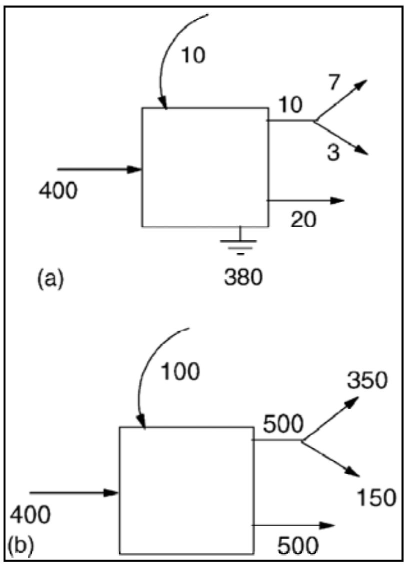
Using emergy to value goods and services has been criticized for ignoring one of the fundamental tenets of economics, which centres on human preference and demand. Cleveland et al. (2000) explain that price differentials are tied to the attributes of a particular good or service. For example, the value of fuels will be linked to physical scarcity, capacity to do useful work, storage amenability, safety, cost of conversion and so on. Consumers will spend more or less resources to appropriate particular goods or services depending on the attributes they find attractive. Emergy analysis consists of converting all goods and services into a common unit of measure so they can be aggregated to evaluate a system's sustainability. Transformity values used to convert energy and material stocks and flows into emergy values may provide some insight into the energetic quality of a particular good or service, but they do not capture those attributes that are linked to economic utility (Cleveland et al., 2000).

This criticism stems from the fact that economics places an anthropocentric value on the goods and services that are generated from natural and human systems. Emergy, on the other hand, provides an eco-centric value by focusing on the supply side of the system. In essence, emergy values goods and services by focusing on what goes into them rather than what someone may be willing to pay for them (Herendeen, 2004). It does so by providing a systems view of our dependence on ecosystems, which is a direct and indirect expression of our reliance on the sun. Hau and Bakshi (2004b) believe that human valuation will eventually have to be more eco-centric if it is to guide humanity toward sustainable development.

Emergy practitioners have tried to communicate the important insights provided by their analysis method by converting emergy units into emdollars. This is accomplished by multiplying an emergy value by a conversion factor, which is the ratio of a particular economy's GDP divided by the total emergy that supports it. This technique has been met with much skepticism from economists who claim that it introduces double counting. In addition, expressing emergy values in emdollars conflicts with the argument that money is an incomplete measure of wealth—an argument that is used to bolster the use of emergy analysis. Nevertheless, this conversion provides a means for communicating the importance of emergy flows to policy-makers, who base their decisions on monetary measurements.

Hau and Bakshi (2004b) state that a lack of formal links between emergy and other thermodynamic quantities such as energy, exergy and enthalpy has fuelled skepticism among energy practitioners. Herendeen (2004) points out one missing quantitative link when he describes how emergy analysis rules lead to systems that do not follow the first law of thermodynamics (the law of energy conservation). Assigning emergy values to all by-products from a system may result in the emergy values going in and out of the system failing to balance. Figure 2.2 shows a system with energy and emergy flows assigned to its inputs and outputs. The energy flows are balanced, while the emergy flows are not. Nevertheless, Brown argues that energy balances typically neglect by-products, or else the process is split into an equal number of outputs to maintain the energy balance (Herendeen, 2004). Both methods contain imperfections, and efforts to benefit from combining both emergy and energy accounting methods are currently underway (Hau & Bakshi, 2004a; 2004b). Although emergy may have some problems fitting into the thermodynamic toolkit, the energy-quality aspect that it brings to energy analysis methods has merit (Hammond, 2007).

Figure 2.2 System input and output values for energy (a) and emergy (b). Reprinted from Herendeen (2004).



Accounting for solar inputs over geological time scales is difficult, if not impossible. For this reason, Hau and Bakshi (2004b) make a distinction between the emergy that is stored and the emergy required for making the stored emergy accessible to humans. For instance, emergy stored in resources such as fresh water and glaciers is calculated by multiplying the global emergy budget by those resources' replacement time (Hau & Bakshi, 2004b). The Earth's sedimentary cycle is used to estimate the emergy required to concentrate natural resources in the Earth's crust so they can be used. For instance, transformities derived for resources such as coal and oil are based on the emergy required to concentrate them in the ore, as opposed to extending the analysis to prehistory. Cleveland et al. (2000) warn that transformity values derived inconsistently could introduce error and lead to discrepancies in the results. Nevertheless, Hau and Bakshi (2004b) argue that the challenge in choosing appropriate temporal and spatial boundaries is universal and necessary for holistic approaches. For instance, life-cycle analysis is typically bounded in some fashion based on a number of criteria that are desirable to the end user of the analysis.

Calculating how much of any one form or energy might have been needed to produce another in the distant past is not an easy task (Hau & Bakshi, 2004b, p. 220). For this reason, Cleveland et al. (2000) argue that the emergy methodology can only partially measure the thermodynamic quality of an energy carrier. One transformity value cannot capture the embodied energy of one class of goods or services. For instance, coal is formed under various conditions and time scales. Applying one transformity value to convert all types of coal to emergy units introduces error in the analysis. Odum (1996) recognizes this shortfall and agrees that each individual product or service will have a unique transformation process. This problem is partially circumvented by deriving a range of transformities for a given product (see Table 2.2).

Allocation within emergy analysis can be confusing, as its accounting rules run counter to conservation equations. Deciding whether flows should be treated as splits or by-products can be difficult. For instance, should different types of rocks be treated as splits or by-products of the Earth's sedimentary cycle? This challenge is actively being worked on and is common to a number of environmental accounting methods. Hau and Bakshi (2004b) propose an algorithm, based on network algebra, that prioritizes emergy-conserving allocations if information on the network and all its products are available.

The emergy method relies on extensive calculations and data that vary in quality and uncertainty. "Averaged transformity of industrial and geological processes are frequently used in specific case studies with no knowledge of the degree of the resulting output" (Hau & Bakshi, 2004b, p. 221). Uncertainties need to be made more explicit and captured in the results. Strong arguments exist for including uncertainty analysis within emergy assessments and many other environmental accounting techniques.

Emergy analysis is also criticized because it hinges theoretically on the largely unproven maximum-power principle, which states that "ecosystems, earth systems and possibly all systems are organized in a hierarchy because this design maximizes useful energy processing" (Hau & Bakshi, 2004b, p. 219). This principle is highly susceptible to scrutiny, as it boldly claims to describe all systems' behaviours and, by extension, the order of the universe. Nevertheless, advances in mathematics and maximum entropy production are giving more validity to the principle (Giannantoni, 2003; 2006; Hau & Bakshi, 2004b). Furthermore, Hau and Bakshi (2004b) maintain that emergy analysis does provide insights on the sustainability of systems and should not be discarded based on a related theoretical supposition.

In general, the research community views the objective of the emergy approach as commendable, but has great reservations about its methodology and application. Emergy analysis is ambitious in its aim to directly connect natural and human systems (Herendeen, 2004). This ambition has opened emergy analysis up to criticism, and Herendeen (2004) deems emergy analysis more likely to fail in its broad policy-making application. Furthermore, Hammond and Winnett (2007) warn that aggregation methods such as the emergy approach need to be used with caution, as they hide important details from policy-makers.

On the other hand, emergy practitioners believe that using the emergy approach to guide policy-making could lead to a more symbiotic relationship between humanity and the natural environment (Brown & Ugliati, 1999). Emergy analysis may provide policy-makers with a more comprehensive picture of the role of ecosystems in the creation of a good or service. "Embodied in the emergy value are the services provided by the environment which are free and outside the monied economy" (Brown & Ugliati, 1999). By using emergy indicators to examine the sustainability of a system, it may also provide valuable insights into whether or not current and forthcoming policies are sustainable.

Hau and Bakshi see the potential for energetic valuation methods to improve decision-making: "Although the final decision is based mainly on economic criteria, thermodynamic methods are crucial for constraining the search space for decision-making" (Hau & Bakshi, 2004b, p. 219). In accordance with the old adage "we can only manage what we measure," the answer may be to use both energetic and economic methods in concert to value EGS.

2.2 Applications

Emergy analysis is applied in a number of ways to assess the goods and services originating from human and natural systems. We examine the application of the emergy approach to assess the sustainability of regional development, agricultural practices, and preservation and restoration of the natural environment. Examining these case studies enhances comprehension of how the concept is being used to assess a system's sustainability and how EGS factor into the assessment.

2.2.1 *Regional*

We examined two regional emergy studies to provide insights about assessing larger spatial systems. Pizzigallo, Niccolucci, Caldana, Guglielmi and Marchettini (2007) used an emergy evaluation of the province of Modena, Italy, to assess the environmental sustainability of the region. Higgins (2003) uses emergy environmental accounting to assess environmental, economic and cultural subsystems of the Oak Openings region in northwest Ohio, United States.

Pizzigallo et al. (2007) assessed the environmental sustainability of the province of Modena, located in Northern Italy, using an emergy approach. The province, which covers a surface area of 2,690 square kilometres, supports food, steel and ceramic industries and has a high population density (242 people per square kilometre) (Pizzigallo et al., 2007). Pizzigallo et al. conducted the analysis 1997 and 2003 to gauge the province's evolution toward sustainability.

The study's authors determined emergy values for energy and materials that were local and renewable (ecosystem services), local and non-renewable (natural capital) and imported into the province. The materials imported into the system were categorized into materials that were locally consumed or transformed for export. In this way the authors identified and analyzed the total emergy flow that fed the system, the total emergy consumed by the system and the total emergy flow exported out of the system. They calculated a set of emergy-based sustainability indicators (EYR, ELR, EIR and ED) for 1997 and 2003 to determine if the province was tending toward sustainable development.

The analysis showed that 27 per cent of the emergy inputs flowing into the province were transformed into exports, while the rest was consumed locally. External emergy flows into the province outweighed local emergy supplies by a factor of 10 to 1. Furthermore, the local emergy supplies consumed consisted primarily of non-renewable resources (99 per cent) as opposed to renewable resources (1 per cent). Comparison of the emergy sustainability indicators calculated for 1997 and 2003 shows that the province was consuming more resources and becoming less sustainable with time (see Table 2.4).

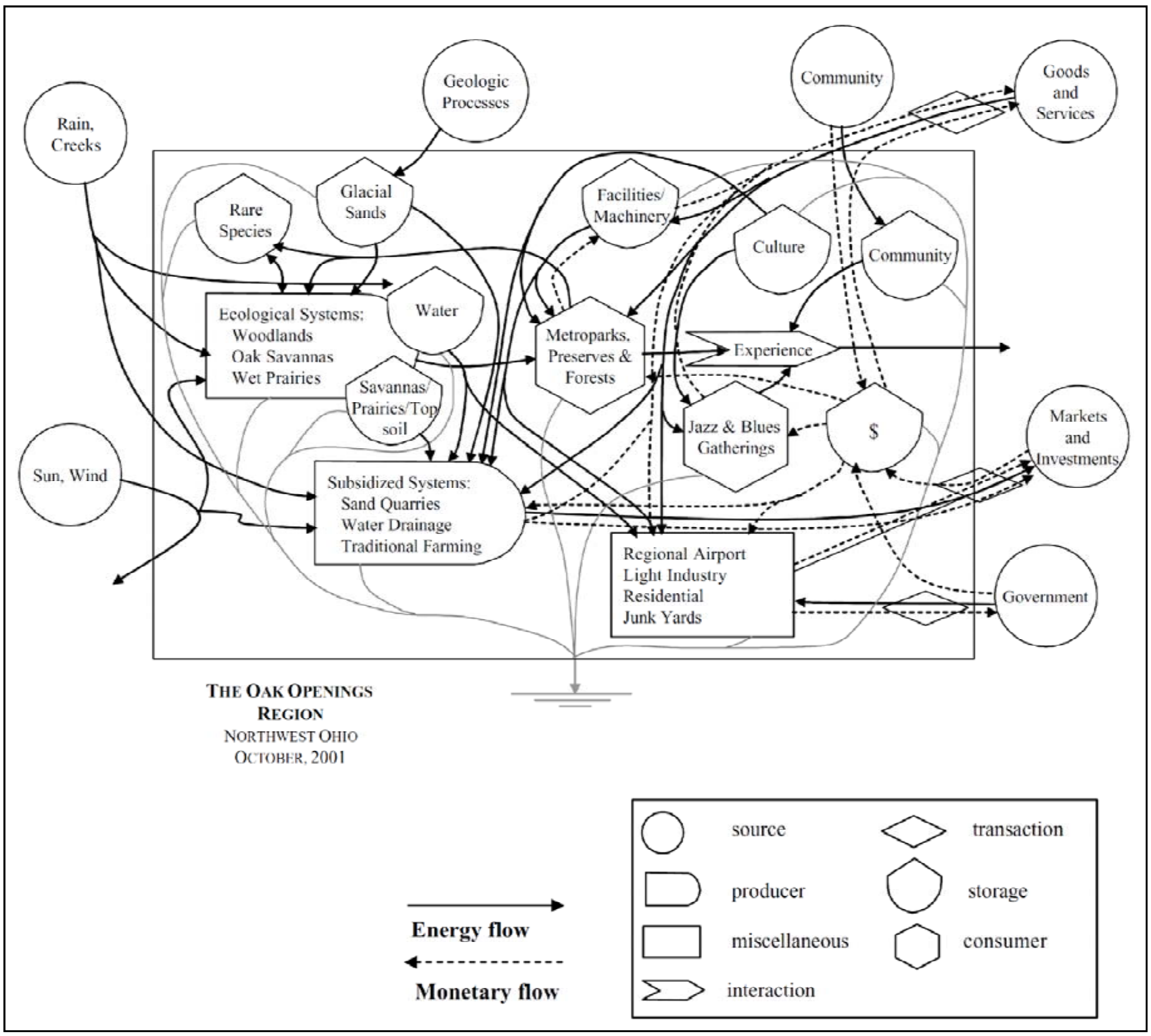
Table 2.4 Emergy sustainability indicators for the province of Modena, Italy, for 1997 and 2003. Adapted from Pizzigallo et al. (2007).

Indicators	1997	2003	Variation (%)
Empower density (sej/m^2/yr)	1.74×10^{13}	2.47×10^{13}	42.1
Environmental loading ratio	79.70	105.85	18.9
Emergy investment ratio	7.05	10.51	48.9
Emergy yield ratio	0.94	0.80	Negligible

The results are indicative of an industrial region dependent on raw material imports to meet its production needs. Measuring the province's emergy imports and exports, with which one can derive emergy sustainability indicators, provides insights to help policy-makers shape sustainable economic and environmental policies for the region (Pizzigallo et al., 2007).

Higgins (2003) used emergy analysis to characterize the environmental, cultural and economic subsystems of the Oak Openings region in northwest Ohio, United States. The Oak Openings region comprises 345 square kilometres on beach ridges and swales. Figure 2.3 shows the environmental, cultural and economic subsystems examined. The site was characterized by woodland, oak savannah and wet prairie ecosystems, which produce stores of water, rare species and topsoil from glacial sands. These natural stores interact with the cultural and economic subsystems of Oak Openings. The cultural features of the site consist of traditional farming activities, maintained natural areas, and jazz and blues gatherings that provide enriching educational and spiritual experiences. The economic subsystem of Oak Openings includes the sand quarries, water drainage, the airport, junkyards, light industries and residential housing.

Figure 2.3 Emergy flow diagram for the Oak Openings region. Reprinted from Higgins (2003, p. 79).



The author analyzed the Oak Openings region by assessing the emergy inputs and outputs, renewable and non-renewable energy sources, and emergy sustainability indicators within and among the subsystems examined. The input-output emergy analysis showed that, overall, the Oak Openings region imported less emergy than it exported. The majority of the region's emergy outputs (approximately 40 per cent) originated from its cultural subsystem (traditional farming, maintained natural areas, and jazz and blues festivals). The natural environments and cultural heritage of the region represent the majority of its total emergy assets, which all three subsystems draw upon.

Higgins calculated four emergy sustainability indicators (EYR, ELR, EI and EM) for the region and compared them with those of its urban neighbour, Toledo, Ohio. Table 2.5 compares three of these indicators. The EYR (1.35) of the region indicates that its activities are sustainable, as the economy is less dependent on resources beyond its border (an EYR of less than one is unsustainable). The ELR, a measure of environmental stress, of the Oak Openings region is quite high and more than double typical ELR values (less than 8) for developed regions. The EI ratio (a measure of the economic emergy sources versus free renewable environmental emergy sources) calculated for the region was 3.80, indicating that the region has a greater efficiency than urban areas. The lower a system's EI the more efficient the system is at using renewable internal emergy sources that can be replenished to feed the system (Higgins, 2003).

Table 2.5 Emergy indicators for the Oak Openings region and Toledo, Ohio. Data from Higgins (2003).

Emergy indicator	Oak Openings region	Toledo
EYR	1.35	0.81
ELR	22.80	-
EI	3.80	26.60

Higgins also carried out an EM analysis to examine the emergy contributions of each subsystem. This provides insights as to which subsystems need to be strengthened to ensure that there is more overall balance and resilience in the system as a whole. The Oak Openings region emergy analysis revealed that the renewable emergy was the limiting factor within the system.

Although the emergy analysis of the Oak Openings region indicates that it exports more emergy than it consumes, the region does so by relying on significant amounts of non-renewable emergy, which is likely to be unsustainable over the long term. The authors caution that the emergy analysis conducted included emergy estimates stemming from the cultural aspects of the region, and such estimates are an area of study that is in its infancy.

2.2.2 *Agriculture*

The emergy approach is being used to assess the sustainability of agricultural production systems at various scales. The spatial and temporal framework, as well as the inputs and outputs used for the emergy analysis, will shape the lens with which agricultural activities are examined. Distilling the inputs and outputs of an agricultural production system to a common unit of measure may facilitate a more holistic comprehension of the system and its sustainability over time. Assessing agricultural systems using the emergy approach can reveal insights for developing sustainable agricultural policies.

We examined three studies to explore the application of the emergy approach within the agricultural sector. Chen et al. (2006) used an emergy approach to examine the sustainability of the Chinese agricultural sector as it evolved from 1980 to 2000. They concluded that the sustainability of the Chinese agricultural sector has weakened as it has moved from a traditional, self-sufficient system to a modernized system. Ortega et al. (2005) evaluated the sustainability of biological versus industrial soybean production systems in Brazil by calculating emergy indicators. The social and ecological benefits and costs calculated using emergy indicators reveal that biological (ecological, organic) approaches are more sustainable than industrial (agrochemical and no tillage with herbicides) ones. Agostinho et al. (2008) used emergy analysis and geographical information systems (GIS) to assess the sustainability of the agricultural practices of three family farms in Brazil. They concluded that agroecological practices are more sustainable than conventional chemical approaches.

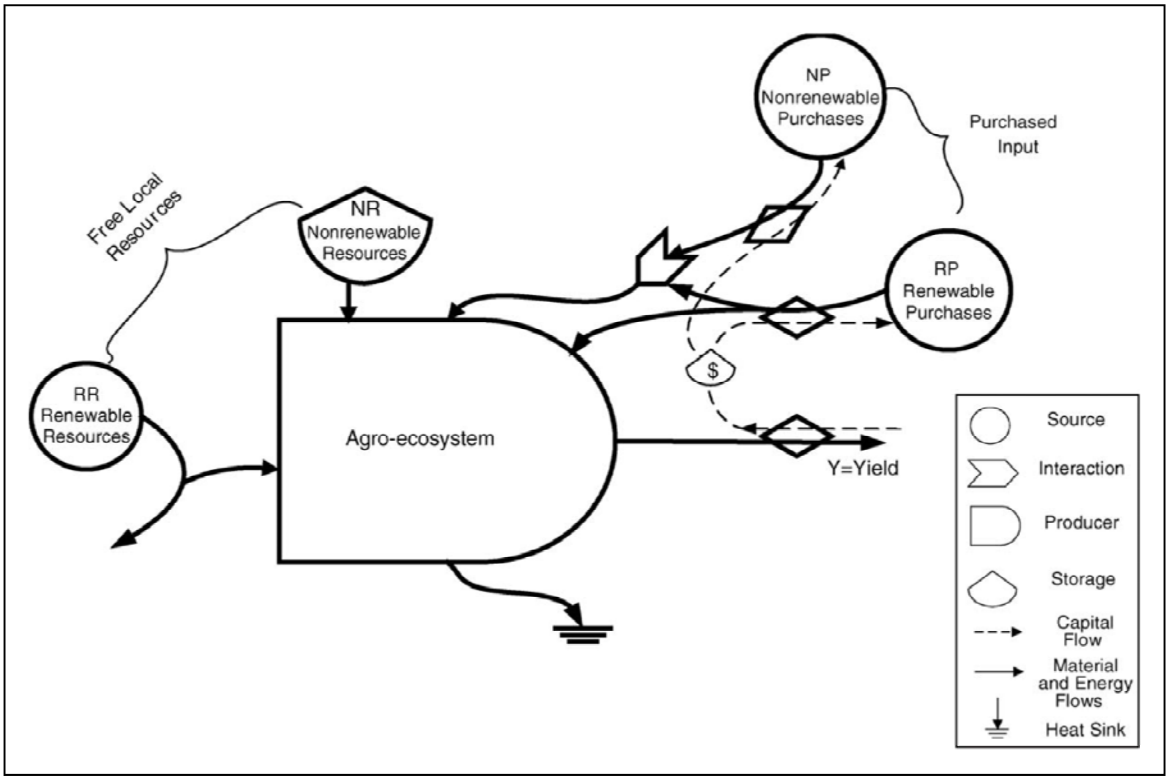
The scope for assessing the evolution of sustainability in the Chinese agricultural system can be considerable. Chen et al. (2006) define the scope by focusing on the Chinese mainland (excluding the Taiwan, Hong Kong and Macau special administration regions) and the following inextricably linked sectors of the Chinese agroecosystem:

- Crop production (grain, rice, wheat, soybeans, corn, tubers, oil plants, sugarcane, beet roots, cotton, vegetables and fruits).
- Livestock production (meat, milk, eggs and wool).
- Forestry (logs, seeds, bamboo and firewood).
- Fishery (fish, shrimp, crab and shellfish.

The authors calculated the emergy values for the inputs and outputs of the agroecosystem. They defined the inputs and outputs as follows (see also Figure 2.4):

- Renewable resources (sunlight, water from rain and irrigation, wind, geothermal and soil nutrients).
- Non-renewable resources (soil lost through erosion).
- Non-renewable purchases (electricity, fuels, chemical fertilizers, pesticides, mechanical equipment, greenhouses, plastic mulch, stables and industrial forage).
- Renewable purchases (water purchased from outside the system boundary).

Figure 2.4 Agroecosystem using energy-system symbols. Reprinted from Chen et al. (2006, p. 163).



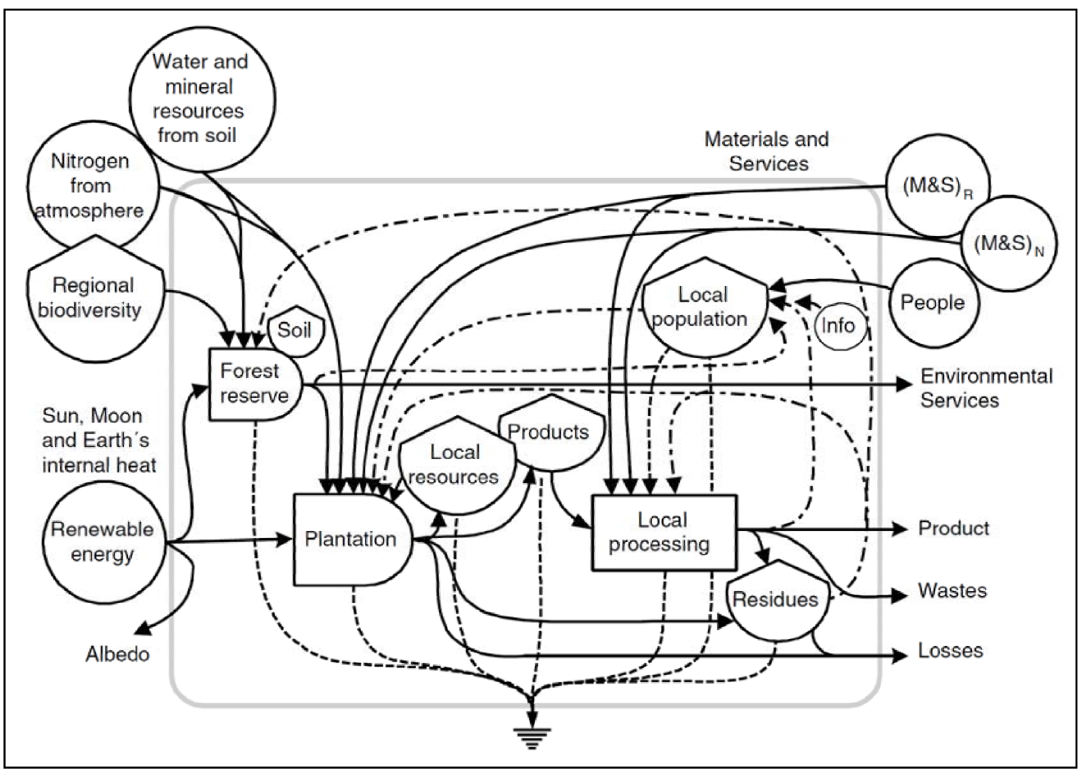
The authors used EYR, EIR, ELR, ESR and ESI indexes to evaluate the sustainability of the agricultural sector over the period of interest. They drew a number of conclusions from the analysis. Both agricultural yields and the average emergy input per unit of land area had significantly increased over time. Although yields increased, all emergy indexes calculated trended toward a weakening of the Chinese agroecosystem (EYR decreased, EIR increased, ELR increased, ESR decreased and ESI decreased over time). Based on the results of the emergy analysis, new policies and directions are required to ensure the long-term sustainability of the Chinese agricultural sector.

Ortega et al. (2005) examined the sustainability of Brazilian soybean production systems using an emergy approach to provide insights for developing sustainable agricultural policies. They assessed the following four soybean production systems:

- Ecological farms, which are typically small, family managed, environmentally friendly and oriented toward subsistence farming as well as supplying markets.
- Organic enterprises, which are larger, labour intensive and environmentally friendly.
- Industrial farms, which are large operations employing fewer people and utilizing chemicals, fossil fuels and machinery that have negative environmental impacts.
- Industrial farms that utilize no-till methods with herbicides, which are larger farms that have negative environmental impacts.

The authors calculated annual emergy inputs and outputs per hectare for each soybean production system (see Figure 2.5). The ecological farm gave the highest emergy yields compared with the other three systems. The authors also computed emergy and social emergy indicators to assess the sustainability of the production systems. The indicators calculated showed that the ecological farm was the most sustainable soybean production system, as it provided the highest emergy yield per input, the most employment opportunities and the lowest externalities.

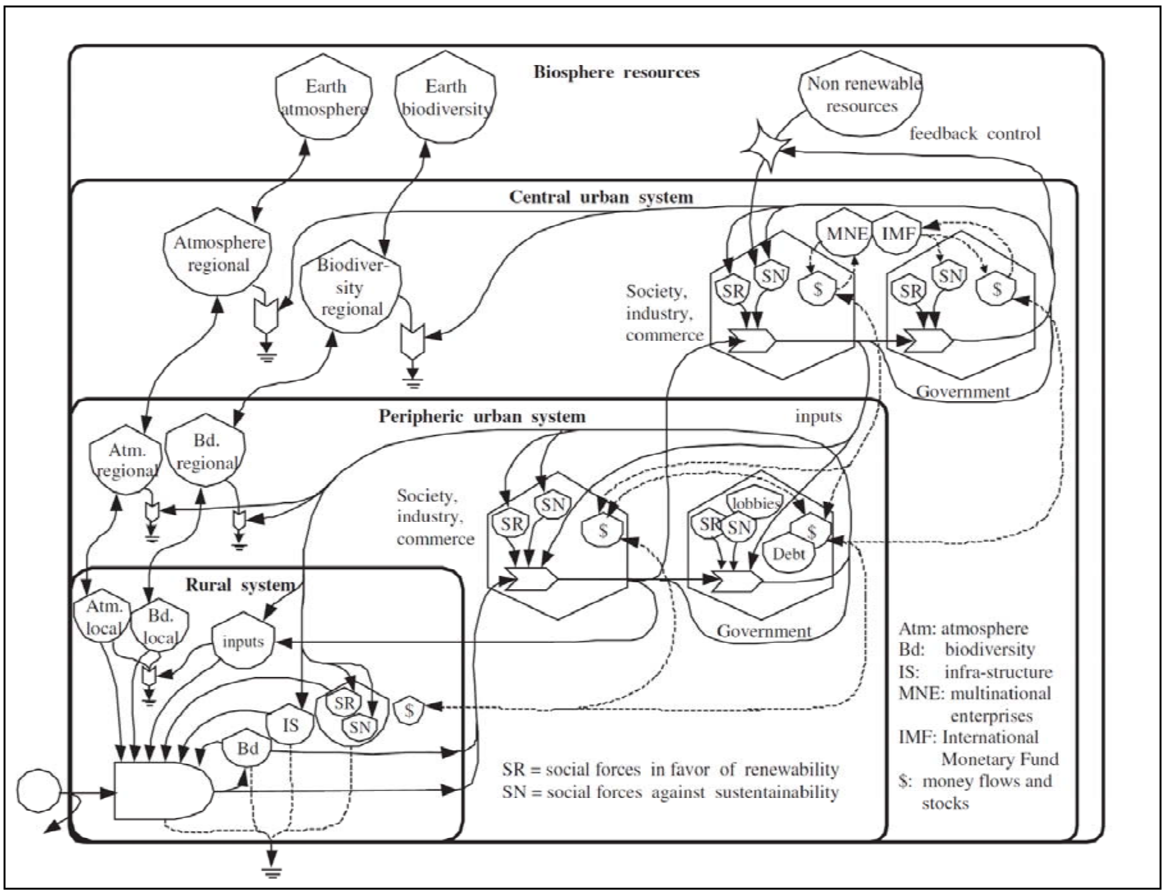
Figure 2.5 Emergy flows for a soybean production system. Reprinted from Ortega et al. (2005, p. 325).



In the Brazilian context the ecological farm benefits the producers directly and society indirectly (Ortega et al., 2005). For these reasons the authors recommend the development of agricultural policies that promote small, family-owned ecological farms as opposed to encouraging large industrial farming for the production of soybeans.

The research also touches on the influences of urban and peri-urban systems on the soybean production systems (see Figure 2.6). The authors identify some of the pressures and influences driving the agricultural sector toward industrial farming.

Figure 2.6 The soybean production system nested within the urban and peri-urban systems. Reprinted from Ortega et al. (2005, p. 332).



One of the main influences they identified was the International Monetary Fund's requirement that the Brazilian government pay its debt by maintaining a high level of exports and lowering social investments. This set up an environment that was conducive to maintaining and promoting an export-oriented agricultural sector that was well-suited for the industrial agricultural model.

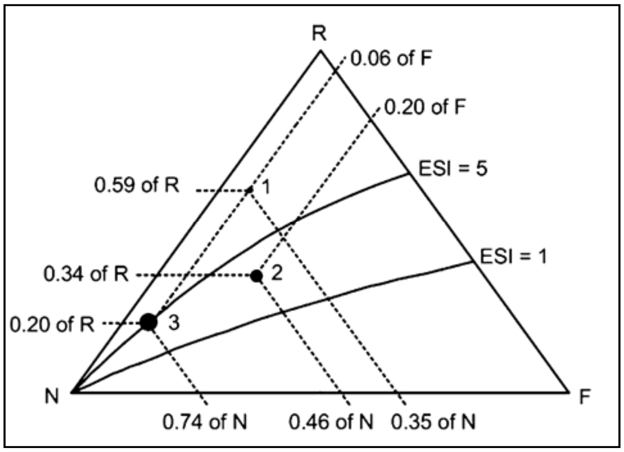
Agostinho et al. (2008) used emergy analysis with the support of GIS to assess farm performance and sustainability. The GIS tool was used to assess topsoil loss using the Universal Soil Loss Equation and rainwater infiltration to estimate aquifer recharge. The renewability of each system input was also examined, and this analysis provided additional information on the sustainability of agroecological and chemical farming practices. The authors used the overall results to assess best management practices and assist with watershed planning. The authors concluded by using ternary diagrams to communicate their results.

The authors evaluated three farms located in Amparo County, São Paulo state, Brazil, using the emergy environmental accounting approach. The farms were the Duas Cachoeiras farm (29.7 ha), which used agroecological practices, and the Santa Helena (15.6 ha) and Tres Lagos (25.3 ha) farms, which used chemical farming practices. These family-operated farms were subject to the same climatic conditions and had similar soil and land-relief characteristics. The authors took the following steps and made the following assumptions to conduct the emergy analysis:

1. Construct a systems diagram showing the inputs and outputs flowing into the system.
2. Assess emergy values for all inputs and outputs of the system.
3. Compile emergy indicators (Tr, %R, EYR, EIR, EER, ELR and ESI) to evaluate the sustainability of the system.
4. Calculate renewability factors for all economic resources used.
5. Calculate soil loss using the Universal Soil Loss Equation and GIS.
6. Assume that macronutrients (nitrogen, potash, phosphorus and limestone) are renewable due to the soil-replenishment practices (such as green manure, compost and organic matter surplus) that are common in Brazil.
7. Assume that water infiltration is another output from the system and estimate it coarsely based on the farms' land covers.
8. Assume that native vegetation biomass is a renewable natural resource flow and estimate it based on the net primary productivity of the farms' land covers.
9. Present the ESI in ternary diagrams (developed by Giannetti et al., 2006).

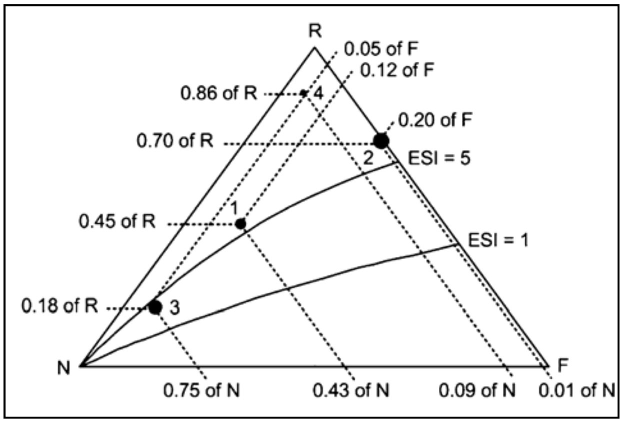
The final results of the study provided information on best management practices that could help improve the sustainability of farming operations. The transformity and renewability ratio calculated for the farms indicated that the agroecological farm was more efficient at transforming potential energy into products and more likely to be sustainable. The Duas Cachoeiras and Tres Lagos farms had the best EYR and EIR scores, which indicates a lower reliance on inputs from outside the system. A closer look at the Tres Lagos farm revealed that the majority of the local resources it consumed were non-renewable, as compared with the Duas Cachoeiras farm. The Santa Helena farm had the highest EER and received the greatest emergy return for the agricultural products it sold in markets. The Duas Cachoeiras farm had the lowest ELR, which is a measure of ecosystem stress. The authors conveyed the ESI using the ternary diagram shown in Figure 2.7. Each side of the ternary diagrams is an axis for the following variables: R = environmental renewable resources, N = non-renewable environmental resources and F = economic resources. The dot size is a function of the emergy used, and the dot location indicates the agricultural system's ESI. The ESI was greatest for the Duas Cachoeiras farm, which indicates that the system's benefit/cost ratio (the benefit to the economy in relation to its environmental impact) is highest.

Figure 2.7 **Ternary diagram showing the results for the Duas Cachoeiras (1), Santa Helena (2) and Tres Lagos (3) farms. Reprinted from Agostinho et al. (2008, p. 48).**



The authors also assessed the emergy of the land covers (annual culture, orchard, pasture and forest) of the Duas Cachoeiras farm. For all emergy indicators that were calculated (Tr, %R, EYR, EIR, EER and ELR), the forest offered the best performance, followed by annual cultures. The authors used a ternary diagram to visually convey the calculated ESI values (see Figure 2.8).

Figure 2.8 **Ternary diagram showing the ESI results for the various land covers of the Duas Cachoeiras farm. Reprinted from Agostinho et al. (2008, p. 50).**



Using the results from this emergy analysis, the authors recommended adopting the following best management practices, which they defined as "the best means of preventing environmental problems while allowing production to be held in an economically efficient manner" (Agostinho et al., 2008, p. 50):

- Reduce and eliminate chemical input usage.
- Establish incentives for farmers to preserve natural forests.
- Use the land correctly based on its properties and climatic conditions.
- Provide certification for farmers that adopt ecological farming practices, so that they can obtain a premium price for their products.
- Consider the agricultural watershed potential and the people in the region.

For policy-makers, the authors advocate the adoption of the following policies:

- Promote agroecological farming practices in critical watersheds to increase water quality and quantity.
- Promote the adoption of agroecology in agrarian reform settlements, as it lowers dependence on external inputs and is environmentally benign.

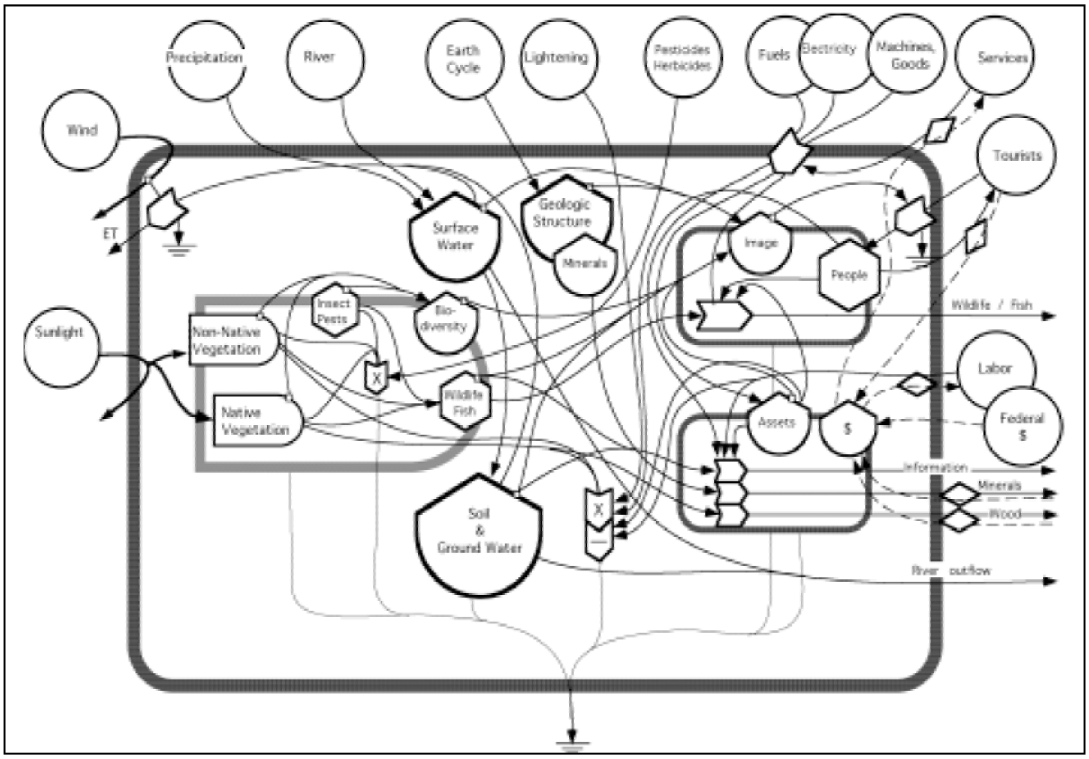
The authors used an emergy analysis to assess where the system might be out of balance with nature. The analysis enabled the authors to suggest farming practices that could improve the overall sustainability of the farming operations. A "spatial emergy analysis" similar to the one conducted on the land covers of the Duas Cachoeiras farm could be used to carry out an emergy assessment of watersheds where researchers have adequate remote sensing imagery.

2.2.3 Natural environments

Trade-offs between interrelated problems involving social, economic and environmental issues are often required to adequately manage natural environments. Brown and Campbell (2007) and Lu, Campbell and Ren (2006) applied emergy analysis to provide additional information for adequately weighing trade-offs to manage natural resources more effectively.

Brown and Campbell (2007) used emergy analysis to estimate the value of the natural capital and environmental services of the nine regions of the U.S. Forest Service (USFS). They evaluated the energy, material and service flows that drove the USFS system, and they also evaluated the system's assets (environmental, economic, geological and cultural) (see Figure 2.9). They analyzed two forests, the Osceola and the Deschutes, to apply the methodology at a smaller scale. The authors chose to express the results in emjoules and in monetary-equivalent emdollars to yield comparable results.

Figure 2.9 USFS energy-systems diagram. Reprinted from Brown & Campbell (2007, p. 45).



The authors calculated the annual emergy driving the USFS in 2005 at ^{em}\$42.7 billion, most of which consisted of renewable environmental flows. Exports from USFS lands (described as "environmental subsidies to the U.S. economy") added up to ^{em}\$263.7 billion. Forty per cent of the export value came from clean water, and 37 per cent from fossil fuels and minerals. Wildlife, wood biomass, hydroelectric power and a range of smaller environmental products accounted for the remaining 23 per cent.

The authors calculated environmental assets in different groupings: environmental, economic, geological and cultural assets. They also calculated the emdollar value of the genetic resources, biodiversity and endangered species on USFS lands (see Table 2.6).

Table 2.6 Value of USFS assets, as reported in Brown and Campbell (2007).

Assets	Value (^{em}\$)
Environmental	$5.7x10^{12}$
Economic	$84.0 x10^{9}$
Geological	$5.7 x10^{12}$
Cultural	$11.4 x10^{12}$
Genetic	$154.1 x10^{15}$
Biodiversity	$209.1 x10^{12}$
Endangered species	$32.7 x10^{12}$

The authors compared the market price of environmental services and natural capital with the emdollar equivalents, though most of the environmental services and natural capital do not have market values (see Table 2.7 for emdollar and dollar values of environmental services). They found the emdollar values they calculated for the environmental services were approximately 8.2 times the market value of the services. They calculated the emdollar value of environmental services without market values to be ^{em}\$52.3 billion, and they found the emdollar value for natural capital was approximately 2.5 times its market value. Natural capital without market values added up to more than ^{em}\$2.8x10^{18}. This value was largely due to the value of geological formations.

Table 2.7 Emergy, emdollar and economic value of services of the USFS system. Adapted from Brown and Campbell (2007).

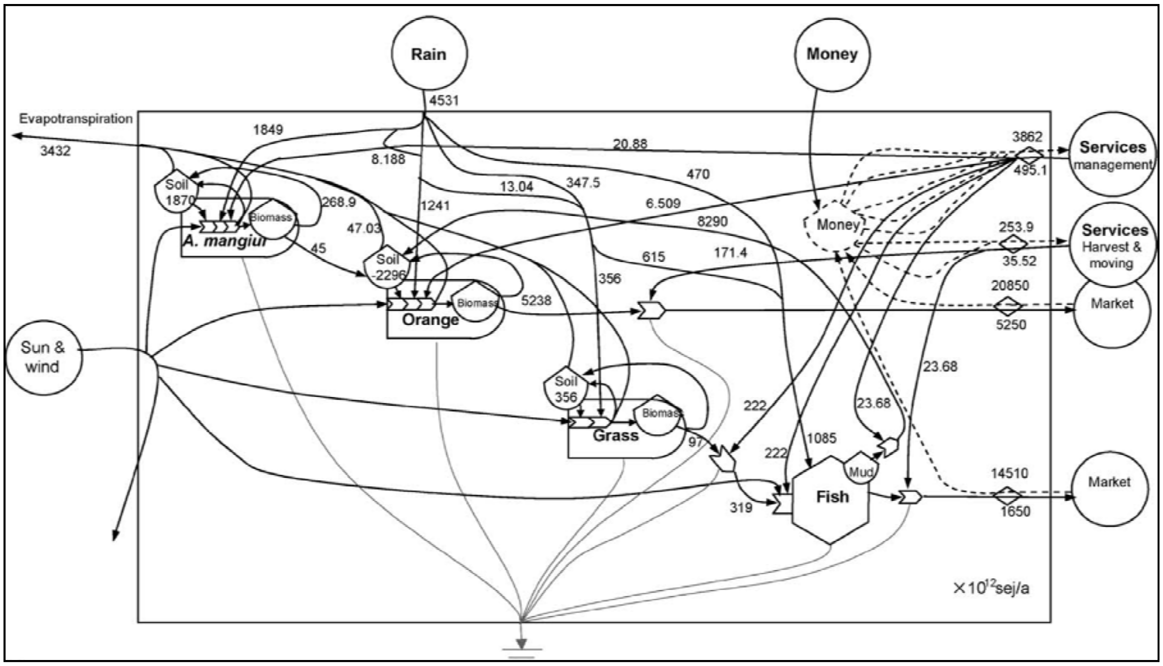
Parameter	Emergy value (10^{21} sej)	Emdollars* (billion ^{em}\$)	Dollar value (billion US\$)
Services with market value			
Research	0.2	0.1	0.02
Organized recreation	2,535.4	1,334.0	9.2
Sales, permits and concessions	5.9	3.1	3.1
Hydroelectric energy	60.7	32.0	11.2
Water supply	101.7	53.6	127.1
Carbon storage	2.4	1.3	1.4
Watershed protection	3.8	2.0	19.9
Wildlife hunting	42.8	22.6	2.9
Fish harvest	1.7	0.9	1.3
Wildlife watching	0.1	0.1	0.8
Total market services per year		1,449.7	176.9
Non-market services			
Clean air	13.2	6.9	-
Clean water	81.1	42.7	-
Pollination	N/A	-	-
Seed dispersal	N/A	-	-
Predator control	N/A	-	-
Gross primary productivity	2.4	1.3	-
Net primary productivity	1.0	0.5	-
Total respiration	1.4	0.8	-
Scientific information	0.3	0.1	-
Total non-market services per year		52.3	0.0

*Emdollars are calculated by dividing the emergy in column three by 1.9 x 10^{12} sej/\$, the average ratio of emergy to money in the U.S. economy.

Overall, the authors found that the USFS annual budget allocation (\$4.9 billion) is miniscule compared with the environmental services (^{em}\$1.5 trillion) and natural resource exports (^{em}\$299.6 billion) provide by USFS lands.

Using an emergy synthesis, Lu et al. (2006) evaluated the benefits of restoring an agro-forest in the most populated and degraded area in China (the low subtropical zone). They did this to investigate the economic and ecological benefits of restoring natural environments and to determine the attributes of this restoration system so it could be further optimized (see Figure 2.10).

Figure 2.10 Energy-systems diagram of the agro-forest restoration system in lower subtropical China. Reprinted from Lu et al. (2006).



The authors conducted the analysis at the system and subsystem levels of the *Acacia mangium* forest–orchard–grassland–fish pond system (developed by the South China Institute of Botany of the Chinese Academy of Sciences) to evaluate the economic and ecological benefits of restoration. They took a wide range of environmental measurements (such as tree height and diameter, soil cores and surface runoff), and extracted management data (such as outputs and service costs) from historical databases.

They created four new indexes to evaluate the economic and ecological benefits:

1. *Emergy restoration ratio*. "The ratio of the total change in ecosystem natural capital storages to the sum of management inputs to evaluate the relative efficiency of restoration for systems with products or co-products staying within the system and resulting in improvements to the environment." (p. 184)
2. *Ecological economic product*. "The sum of any increase or decrease in the emergy storages of ecosystem natural capital plus the emergy of the yield taken out of the system or subsystem under analysis." (p. 179)
3. *Emergy benefit ratio*. "Ratio of the ecological economic product to the sum of purchased inputs to the production system. It measures the ecological and economic efficiency of the emergy applied in a production system as a result of human behaviour." (p. 184)
4. *Emergy benefit after exchange*. "Represents the net benefit received by a system as a consequence of economic production and trade" (p.185); "The ratio measures the state of the system as determined by market exchange." (p. 180)

The authors found the emergy exchange ratio to be lower than one for the grassland subsystem, indicating that the system was losing wealth as its above-ground biomass was mowed, with high labour costs and without feedback to the subsystem. In contrast, the emergy exchange ratio was above one for the orchard and fish ponds, indicating that these subsystems were gaining wealth. Tree biomass and the environmental services provided by the trees exceeded declining soil productivity, and the sale of pond fish gave substantial returns.

The authors stated that further multilevel studies were needed to optimize the system, though they identified areas for improvement. They suggested, for instance, that the introduction of duck breeding to the system would improve sustainability, because the ducks would reduce the labour costs of cutting and mowing grass, their droppings are good fish forage, and their swimming action can increase the dissolved oxygen concentration of the pond. This study enabled the authors to investigate the environmental and economic benefits of restoring natural environments and explore how to optimize the restoration process.

3.0 Expert interviews

We conducted six semi-structured interviews with experts who were either proponents or opponents of the emergy approach (see Appendix C). The following interviewees all hold doctorate degrees and have published articles related to energy, emergy and the valuation of EGS in peer-reviewed journals:

Proponents: Dan Campbell, David Tilley, Mark Brown

Opponents: Geoffrey Hammond, David Herendeen, Robert Costanza

We conducted the interviews in an informal fashion to promote a free flow of information between the interviewer and interviewee. The questions centred around two major themes: the scientific robustness and the policy relevance of the emergy approach to valuing EGS. We used a questionnaire strictly to maintain the discussion and ensure that the major themes were adequately explored (see Appendix C).

We recorded the interviews, whose length ranged from approximately 45 minutes to one hour. We reviewed the recordings to extract the insights that were shared during the interviews, and we sent summary notes to the interviewees to confirm that the information was interpreted correctly. We have compiled the summary notes and present them here under the following headings: scientific robustness, policy relevance and next steps.

3.1 Scientific robustness

We discussed the scientific robustness of the emergy approach in general terms with the interviewees, who shared a number of concerns and misconceptions related to the approach. They generally agreed that the data required to conduct an emergy analysis is available, but their opinions differed regarding the quality of the available data and the soundness of the method. In general, all interviewees considered the endeavour to develop a system of environmental accounting based on solar energy commendable. Dr. Herendeen stated, "A world based on energy flows would be more sustainable than the world today."

Emergy proponents believe that the maximum power principle and emergy approach can be powerful concepts that can help guide decision-making, as they provide insight into nature's decision-making process. They view the emergy method as scientifically robust and useful, but with room for future improvements. On the other hand, opponents state that the maximum power principle is a circular argument that has not been adequately proven or explained. Nevertheless, Dr. Campbell pointed out that Giantonni is making advances toward mathematically proving the maximum power principle. He maintains that "just because every aspect of the theory has not been proven, it does not mean that you throw it away and say it is wrong."

Views on data availability were fairly consistent among all interviewees, but views on its validity and applicability varied. Published transformity values were revised in 2002, and emergy data is available depending on the system and components being examined. For instance, there is good information on forest processes and water flows, but there may not be for assessing specific exotic species. The required transformity values can be generated using defined methods. Emergy proponents contend that the methods used to develop emergy signatures and transformity values are scientifically sound and estimated based on information obtained from the literature.

Emergy opponents maintain that transformity values are derived by mixing apples and oranges. The time scales used to derive transformities are not consistent. For example, geological timescales are used to derive transformities for fossil fuels and mineral ores, while decades are used for deriving transformities for forests. In addition, stocks and flows are being mixed, which leads to dubious results. Emergy proponents agree that published transformity values need to be revisited to take into account technological advances and human-influenced changes occurring in the geobiosphere, such as climate change. Dr. Campbell points out that only a small number of people are working in emergy, and the number of things to be done far exceeds capacity.

The interviewees expressed some concerns in terms of the directionality of emergy analysis and whether it aims to minimize or maximize emergy flows. Dr. Campbell explained that, in general, the goal is to make the same thing with the minimum amount of emergy. The transformity value for shrimp production in the Gulf of Mexico in a natural system is about a quarter of the transformity of intensive shrimp farming in Ecuador.

Dr. Tilley mentioned that ecologists, economists and energy analysts are criticizing the emergy approach. Economists who neither believe in nor have an appreciation for energy laws do not put much faith in biophysical measurement methods. Converting emergy values to emdollar figures has helped to communicate emergy analysis results, but the practice is highly criticized by economists. Ecologists hesitate to embrace the concept, because they see the world as random and chaotic, while emergy is predictive. Energy analysts have a problem with the accounting approach, which seems to violate the first law of thermodynamics.

Economists and psychologists have an additional layer of knowledge over and above and understanding of the physical function of our environment, and this added perspective can be important. A number of biophysical approaches fall short because they lack social and economic aspects, which can greatly influence the results of an analysis, while the emergy approach can integrate and account for these aspects. Dr. Tilley also added that the emergy approach does not violate the first or second laws of thermodynamics, but runs into accounting problems such as allocation—a problem that is shared by all other systems-accounting techniques.

The emergy method does have the advantage that it takes into account all energy inputs, compared with conventional energy methods, which are really based on fossil fuel accounting. According to Dr. Hammond, applying the emergy approach in systems such as agricultural systems, where there is a high level of human and natural interaction, would yield interesting results.

Emergy proponents believe that using an emergy approach to value ecosystem services is more adequate than using economic instruments, as the services are public goods. Dr. Brown stated that a donor-based system is required to value public goods. Emergy opponents maintain that the only way to adequately value EGS is by using a toolbox or a plurality of methods. Dr. Hammond stated, "There are a lot of things unrelated to energy that should be of concern when assessing ecosystems." He believed that emergy analysis could only be useful in assessing a system's energy flows and that integrating various sources of information by expressing stocks and flows as solar energy introduces inaccuracy. He supported his position by mentioning that aggregating values from different methods leads to inaccuracies because the methods have different error bands. Furthermore, aggregating results from various methods may hide important details from decision-makers. Dr. Herendeen maintained that "one single indicator will likely not work for everything."

Emergy opponents maintain that a number of other, more rigorous techniques are much more suitable for valuing EGS. These methods include net energy, ecological footprint and net primary production analysis. The U.S. EPA will be releasing a report shortly summarizing EGS-valuation best practices. These will include net energy analysis, which is viewed as more defensible but also more data intensive and time-consuming than the emergy approach. Nevertheless, all ecosystem service–valuation techniques have their problems. Dr. Costanza supported this thought by stating that "both economic and energetic approaches mean something, but neither provides the full answer, and you are better off doing both to get a pluralistic view." He agrees that there may be some potential for emergy to provide some general insights, if all assumptions and uncertainties are clearly stated and other emergy values exist for comparative purposes. However, he maintains that using net energy analysis is clearly advantageous due to its methodological rigour and acceptance as compared with the emergy approach.

3.2 Policy relevance

In general, both emergy proponents and opponents agree that more biophysical measurement methods need to be infused into the policy-making realm. According to Dr. Costanza, energetic measurement methods are not being used to guide decision-making. Dr. Herendeen stated that "biophysical measurement methods are creeping into the policy-making, and it is appropriate to get more of these methods out to policy-makers." Dr. Brown argued that the lack of biophysical measurement methods within policy-making exists because policy-making is primarily human centred and because we are not told that the natural environment is the basis for all wealth. The U.S.

EPA report on EGS-valuation best practices, which includes net energy analysis, may help clear a path for integrating EGS-energetic valuation methods.

Emergy proponents believe that emergy analysis is a good tool for valuing EGS and environmental debt. Furthermore, it could be used to establish a system of payments for ecosystem services. Dr. Tilley believed that it could be used effectively to set prices for ecosystem service bundles by evaluating a number of ecosystem services using a common unit of measurement. In addition, emergy is a useful tool for assessing ecosystem services that are often perceived as invisible, such as supporting services. The emergy approach is not limited to solar energy, but also includes tidal energy and deep heat. Dr. Brown stated, "I don't know of any other methods that use geobiosphere processes to evaluate goods and services." He maintained that the true value of the environment cannot be captured by valuing EGS using economic instruments. Energy analysts never get back to the environment, and economists go around asking people how much something is worth.

On the other hand, emergy opponents believe that the emergy technique may be of some use for looking at energy and material flows, but not much else. Costanza (2008) has contended that the method used for emergy analysis is idiosyncratic and does not follow the basic accounting principle of additivity. Dr. Herendeen maintained that, along with the economic view that natural resources are freebies, the emergy approach is flawed because no method can capture energy flows over geological time scales. "The solar energy required to convert biomass into fossil fuels does not have meaning, because energy flows over geological time cannot be captured," he said. Furthermore, he added that the concept of a solar economy implies that we would be living strictly on flows, not storage.

Dr. Costanza believed that we need a plurality of approaches to adequately value EGS and that energetic and economic valuation approaches are a good place to start. Dr. Hammond believed that it is important to draw out, from the different tools or methods in the toolbox, the important results that are of concern to decision-makers. Statutory and regulatory agencies must facilitate the adoption of a plurality or a toolbox of methods to support decision-making. Dr. Hammond added that "it would be useful to assess what decision-making tools are being used by environmental agencies, to facilitate matching adequate tools for a given department." Economic instruments fall short of valuing supporting services, and this would be a good way to justify using energy approaches to value EGS.

Emergy proponents and opponents alike believe that economic and energy approaches can be complementary in valuing EGS. Emergy proponents believe that emergy analysis is useful for examining economic systems. Dr. Campbell stated that the emergy approach will not supersede other approaches, because these are required for understanding all parts of a system. "The emergy approach integrates instead of disposing [of] information." Dr. Tilley advocated making a clearer distinction between public and market-traded dollars, and Dr. Campbell believed that a double-entry bookkeeping system that tracked economic and environmental considerations would be an effective way to value natural environments.

The emergy approach does not necessarily convey environmental limits explicitly. Dr. Brown stated that a lot of work is being done to communicate environmental limits by calculating and reporting a number of emergy ratios, such as the environmental loading ratio, and that regional emergy requirements can be compared with global emergy requirements.

Emergy proponents believe that the emergy approach currently does not have traction in policy-making because it is complex and policy-makers do not have time to understand it. In addition, policy-making is human centred, and valuation is primarily based on anthropocentric values and utility. Dr. Tilley agreed that emergy analysis needs to be made simpler to understand and calculate. For this reason he is developing a rapid emergy-assessment method. Dr. Brown stated that fifteen-minute movies may be the most effective way to communicate the concept to policy-makers. Conveying the concept in the simplest manner is crucial for gaining acceptance.

According to Dr. Brown, practitioners conducting emergy analysis try to be completely transparent so that the data utilized, the assumptions made and the calculations remain explicit. Dr. Brown believed that when compared to the ecological footprint, the emergy approach is more transparent, as ecological footprint conversion factors typically remain unpublished.

Emergy opponents believe that, in addition to being complex, the emergy concept is confusing. Dr. Costanza contended that, in general, communicating ideas related to embodied energy to decision-makers is very difficult, and introducing emergy would only add confusion, as it does not follow the first law of thermodynamics. He states that "even people who have a background in the natural sciences have a problem with understanding emergy." Emergy proponents describe this issue as an allocation problem, as co-products are evaluated separately and should not be added up when conducting an emergy analysis.

Dr. Hammond reasoned that policy-makers may not have the educational background to understand the concept. "The civil service in the U.K. does not have the right background [human sciences as opposed to natural sciences or engineering] to understand concepts related to emergy."

Dr. Costanza explained that decision-makers may have to defend their decisions in court, making the use of well-accepted EGS-valuation best practices ever more important. He states that decision-makers "may have to go in court and make statements on the best information they have, which in some cases may be inadequate within a legal context."

Systems thinking is required to make the emergy approach more acceptable. The emergy approach has been applied in many different countries (China, Taiwan, Korea, Italy, Australia, Brazil, Sweden and the United States). Specifically, it is being used prominently in Italy to examine and guide regional development. Dr. Campbell believed that Canada would be a natural place for the emergy approach to flourish, because of the country's long history of using systems thinking to address various issues, such as remediating the Great Lakes.

Emergy proponents believe that it is crucial to present the emergy concept to open-minded people with decision-making power and the financial resources to undertake an emergy analysis. Dr. Campbell mentioned that the U.S. EPA has been willing to listen and support the development of the concept by supporting post-doctoral students who are working on moving the concept forward. Dr. Herendeen believes adopting the types of methods that are being covered by the media and that people can understand is effective, because politicians are more likely to take notice. According to him, the ecological footprint seems to be well understood and accepted by the public. Dr. Hammond rightly pointed out that emergy has only a small number of supporters, and this must be kept in mind if there is interest in investing in the technique.

3.3 Next steps

We asked all interviewees what they thought would be a good way for Alberta Environment to proceed with respect to using EGS to guide the province's development. Their responses varied and were consistent with their positions on emergy.

Two opponents of the emergy approach clearly supported Alberta Environment's efforts to integrate EGS into decision-making related to the province's development. Dr. Herendeen stated that "the goal of trying to quantify and qualify ecosystem services is the right one." They also advocated going beyond economic instruments to capture the value of EGS more comprehensively.

Dr. Costanza and Dr. Hammond recommend using a toolbox or a plurality of approaches to value EGS. They acknowledged the emergy approach as potentially useful for providing insights, if the assumptions and uncertainties used in the analysis were made explicit. Nevertheless, emergy opponents were of the opinion that net energy, ecological footprint and net primary production would be more appropriate, as they are likely to yield results that are more accepted and accurate.

Dr. Costanza suggested that we broaden this emergy study to examine other energy-related methods that could provide important insights for valuing EGS. This recommendation is consistent with an upcoming U.S. EPA report that calls for a pluralistic approach to valuing EGS and includes net-energy analysis.

Efforts to value EGS should include complementary top-down and bottom-up approaches. This way, ecosystem services that are important and less visible to the community will be identified and adequately valued. Stakeholder engagement is important to guiding an EGS analysis because it would likely expand the EGS-valuation scope beyond economic instruments.

Emergy proponents called for a much broader approach, going well beyond EGS, to guide the province's development. The emergy proponents suggested a systems and adaptive approach encompassing activities such as stakeholder consultations and modelling. For this reason, Dr. Brown recommended that the first logical step would be to bring in high-powered systems scientists to assist with the process.

Conducting an emergy analysis could support and complement a more comprehensive systems approach. For instance, doing a valuation analysis of ecosystem services side-by-side with economic instruments and emergy could yield interesting insights, as services of little economic value may have an important emergy value. Dr. Tilley also suggested that a rapid emergy assessment method, which he is currently developing, could yield important information with less data requirements and expenditures.

Dr. Campbell advocated moving away from a services approach to a double-entry bookkeeping method, which would focus on economic and environmental assets and liabilities. He felt that this would provide a more complete picture of impacts related to potential developments compared with EGS, which cannot all be monetized and incorporated into an analysis.

To continue exploring the emergy approach, the emergy proponents suggested we organize a group of experts, including government representatives, to discuss the strengths and weaknesses of the method. This would yield additional insights and provide an opportunity to challenge aggregation methods. Dr. Hammond felt that aggregation is not favourable, as it often hides important details from decision-makers.

Emergy proponents believe that to initiate more emergy-related work it is imperative to communicate the concept to open-minded, empowered decision-makers who have access to the financial resources required to conduct an emergy analysis. Dr. Campbell mentioned that emergy analysis has to be seen as important enough to be included in the mix of decision-making tools that are currently being used.

Dr. Campbell believed that once there is buy-in, the emergy approach should be applied to a problem where it can make a difference. Dr. Hammond stated that testing the emergy approach using one or two case studies along with other techniques would be useful for comparison. Similar and dissimilar results obtained from the various methods used will provide decision-makers with more or less confidence in the information provided by the assessments. The methods and results could then be peer reviewed.

3.4 Summary

In general, both emergy proponents and opponents agree with the general objective of the emergy approach. The polarized views obtained originate from differences of opinion on the emergy analysis methodology. Proponents believe that it is scientifically sound, while opponents believe that it is flawed.

Everyone was in favour of using more biophysical measurement methods to assess and value EGS and guide decision-making. Emergy proponents argued that the emergy approach is adequate for valuing EGS because it is a donor-based system that is adequate for valuing public goods. Emergy opponents do not believe that the emergy analysis methodology is sound, and they advocate for using net-energy analysis, ecological footprint and net primary production to value EGS. A U.S. EPA report outlining EGS-valuation best practices, to be released shortly, advocates for a plurality of EGS-valuation approaches that include net-energy analysis.

The emergy approach is complex, and policy-makers may not have the time or the educational background to grasp the concept. In addition, emergy opponents believe that it adds additional confusion to using energy-based methods, as it does not follow the first law of thermodynamics, which implies additivity. Emergy proponents claim that the emergy approach follows both the first and second laws of thermodynamics, and that the lack of additivity is rather an allocation issue that is shared by all other system accounting methods.

Potential next steps for Alberta Environment include expanding the scope of this study to include other energetic valuation methods, organizing a workshop with proponents and opponents of the emergy approach to gain additional insights with respect its potential suitability for valuing EGS, and evaluating case studies using both the emergy approach and economic instruments to compare and contrast the results. This evaluation should be peer reviewed.

The interviewees also suggested more broadly that a systems approach is required to guide the Province of Alberta's development. Such an approach would include other considerations beyond EGS. Emergy proponents recommended bringing in high-powered systems scientists to help guide the process, to adopt a double-entry bookkeeping system to monitor environmental as well as economic assets and liabilities, and to initiate stakeholder consultations and conduct modelling exercises.

4.0 Online survey

The purpose of the survey was to determine the potential uptake of emergy analysis for valuing EGS among former IISD interns and students as well as graduates of environmental and natural resource management programs (referred to as "target groups"). Specifically, the target groups consisted of students and alumni from the following internship and degree programs:

- School for Resource and Environmental Studies (Dalhousie University). This graduate management program uses inquiry and ethical practice to inculcate responsible environmental and natural resource management.
- Master of Environment and Management (Royal Roads University). This graduate program aims to develop knowledgeable and effective professionals and leaders in environmental sustainability.
- School of Resource and Environmental Management (Simon Fraser University). This school offers graduate interdisciplinary programs in resource and environmental management.
- Natural Resources Institute (University of Manitoba). The institute offers graduate programs promoting interdisciplinary knowledge in the areas of environmental and natural resource management.
- Engineering and Society Program (McMaster University). This undergraduate program examines the complex interactions between technology and society.
- IISD Internship Alumni Network. This program provides young professionals with the skills and experience to become effective change agents and develop sustainable development policies.

We selected and approached the target groups to try and get a general geographic representation of the country. Ultimately the main determinant influencing the selection of the target groups was the willingness of the various alumni distribution list administrators to assist with the research.

4.1 Methodology

We developed the survey and posted it on Survey Monkey (www.surveymonkey.com), an online survey Web tool that allows users to build surveys, host them online and record data. We contacted prospective participants via alumni email lists and directed them to the online survey via a Web link. Aside from collecting demographic information, we tested four variables:

1. Has the target group heard of emergy analysis?

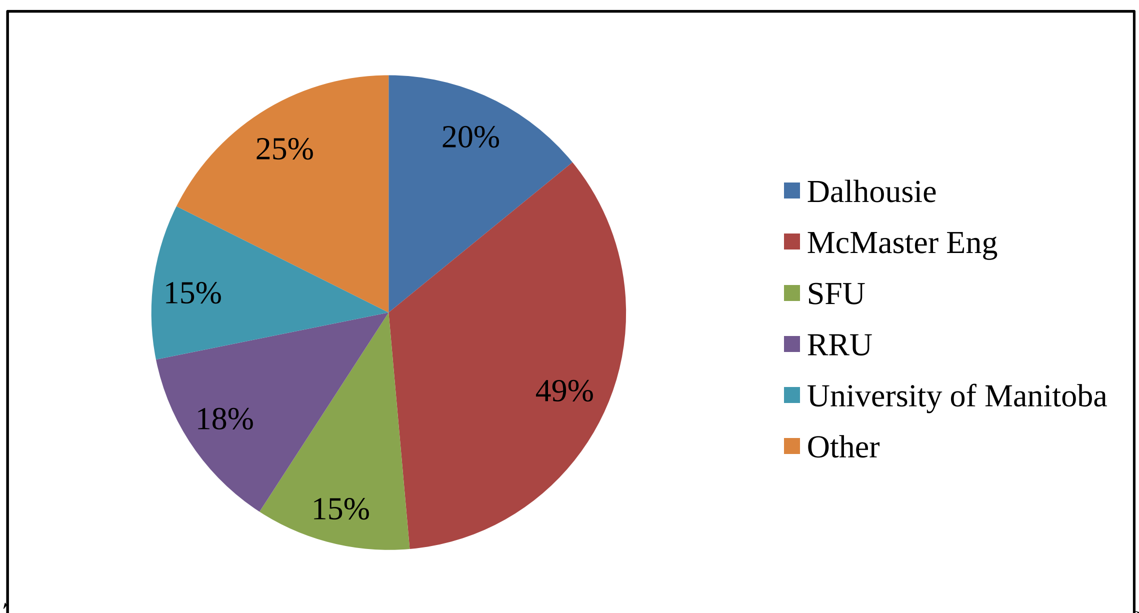
2. Has the target group heard of other methods for valuing EGS?
3. Does the target group see value in using emergy as a decision-making tool?
4. Does the target group believe that approaches for decision-making ought to be based more on biophysical measures than they currently are?

We collected the results through Survey Monkey and analyzed them using Excel. The survey questions and associated results are provided in Appendix D.

4.2 Results and discussion

More than 135 people responded to the survey, and 119 people completed it. Many respondents were familiar with techniques for measuring EGS, and 17 per cent of respondents reported that they had previously heard of emergy analysis. We did not determine the statistical confidence and precision of the survey, because the total population size (and therefore response rate) was unknown. While it would be possible to obtain the number of email addresses on each email list, these figures are not necessarily representative of the number of email recipients. Depending on the list, a significant fraction of the addresses may be inactive or duplicates. There is also overlap among different email lists, and it was not possible to determine the extent of this overlap among groups. The effort required to determine the statistical confidence and precision of the survey was not feasible within the scope of the project. We interpreted the results qualitatively, and they should be used with caution.

Figure 4.1 Breakdown of survey respondents.



questions,

such as age and education. The second section gauged respondents' opinions on the degree to which decision-making is currently based on economic or biophysical measures and whether it ought to be more or less so. The third section explored respondents' level of knowledge on EGS and methods to value them. The fourth section explored respondents' opinion on emergy analysis (Is it too complicated? Is it understandable? Is it useful for decision-making?). The final section consisted of two open-ended questions and two yes/no questions to determine sampling biases. We discuss the survey results for each section, with the exception of the background questions, in the following subsections.

4.2.1 *Decision-making*

The purpose of this section was to determine the degree to which respondents perceived decision-making to be based on economic versus biophysical measures, and whether they believe it ought to be more or less so. The respondents indicated that they believed decision-making at present is largely based on economic measures, as opposed to other (such as biophysical) measures (85 per cent agree versus 13 per cent disagree), and that tools for decision-making related to natural resource management should be more based on biophysical measures than at present (87 per cent agree versus 11 per cent disagree). The specific questions asked and the associated results can be found in Appendix D.

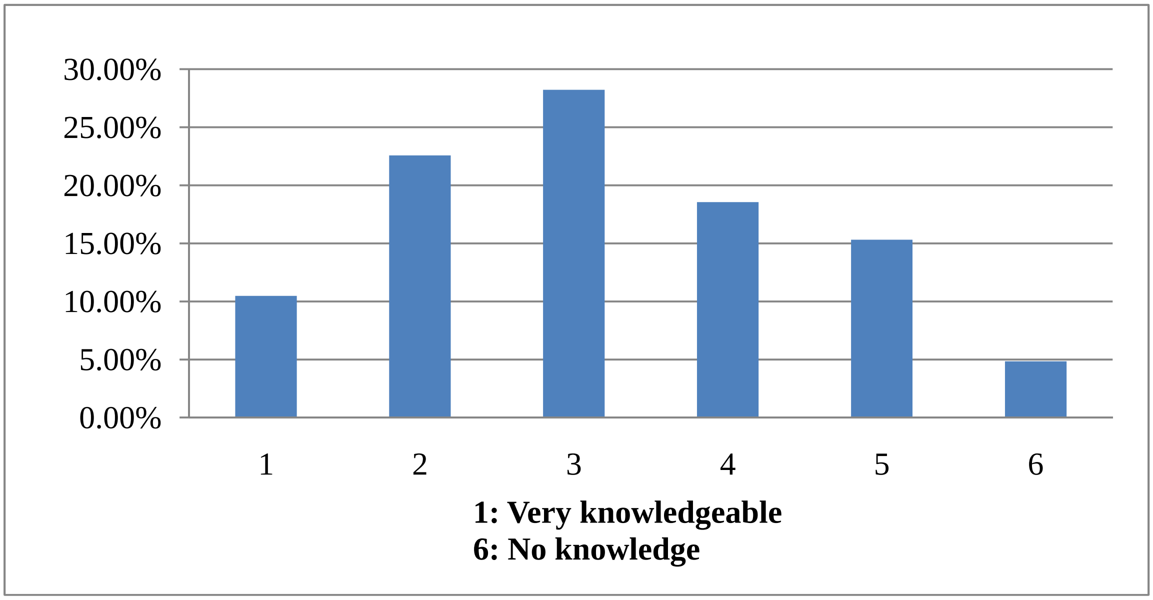
4.2.2 *Ecosystem goods and services*

The questions in the EGS section of the survey were designed to explore:

- The level of respondents' EGS knowledge.
- If respondents had heard of emergy analysis.
- If respondents had heard of other EGS-valuation methods.
- If respondents thought familiarity with EGS-valuation methods was something that would be useful for them in the future.

We found respondents' stated knowledge of methods to value EGS to be well represented by a bell curve skewed slightly toward the knowledgeable end of the spectrum (see Figure 4.2). The distribution is quite broad, with 10 per cent of respondents rating themselves as very knowledgeable, and 5 per cent at the low end of the spectrum, with no knowledge of EGS-valuation methods.

Figure 4.2 Knowledge of EGS valuation methods among respondents.



Interestingly, respondents with an educational background in the natural sciences, social sciences and management reported themselves as very knowledgeable about methods to value EGS more than twice as frequently as respondents with an educational background in engineering. Approximately three-quarters of respondents with educational backgrounds in management (76 per cent) and natural sciences (75 per cent) reported themselves as between one and three (where one is very knowledgeable and six is no knowledge), compared with 63 per cent of respondents with a social sciences background and 48 per cent with an engineering background.

Almost two-thirds of respondents indicated that they were aware of methods for assessing EGS values. The most recognized methods of valuing EGS were contingent valuation (46 per cent), market pricing (46 per cent) and replacement costs (34 per cent). Emergy analysis was the method least recognized by the respondents (11 per cent). This finding is supported by question 15, which found that 14 per cent of respondents had previously heard of emergy analysis. The majority of respondents (97 per cent) believed that knowledge of methods to evaluate EGS is something that they may find useful in the future.

Results could be biased, as it is possible that the questions were insufficiently precise and were interpreted differently by students and practitioners of different disciplines. For instance, the context in which the term "knowledgeable" is interpreted may be different for each discipline; knowledge about methods for valuing EGS might be interpreted by engineers to be of a more technical nature, concerning how these methods work, whereas social scientists might consider general familiarity with the tool and its associated results as knowledge.

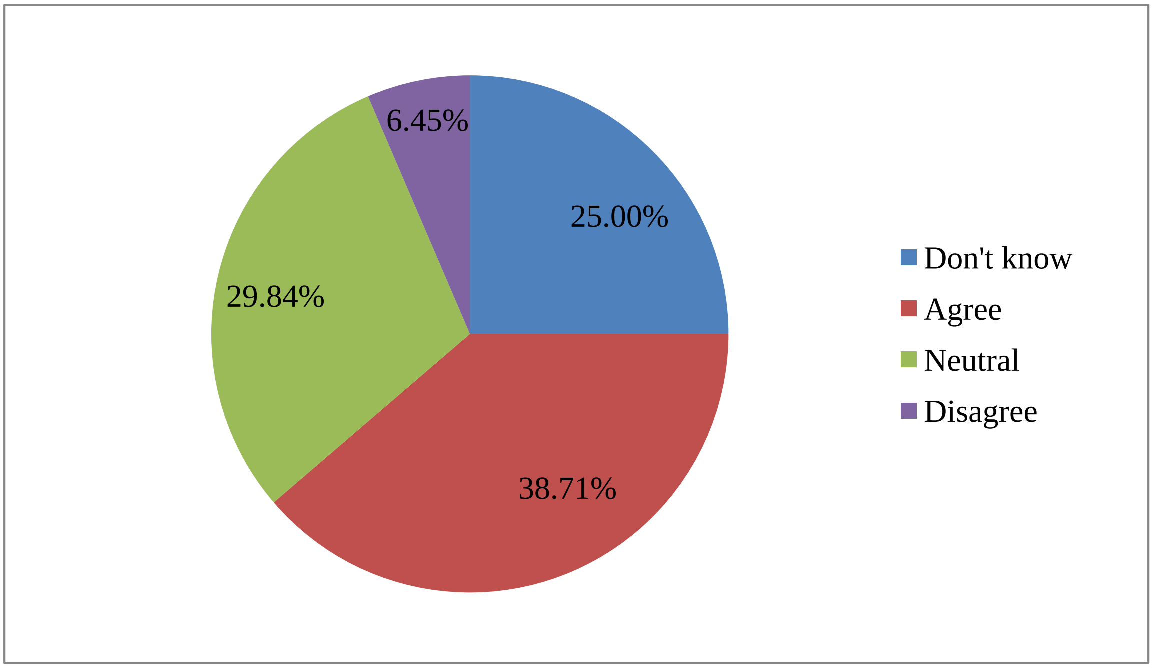
4.2.3 *Emergy questions*

The purpose of this section was to find out if respondents had previously heard of emergy analysis and to get their perspective on its usefulness as a decision-making tool.

Overall, only 14 per cent of respondents indicated that they had previously heard of emergy analysis. Respondents with backgrounds in the social sciences or management indicated that they had heard of emergy analysis significantly more frequently (22 per cent and 20 per cent, respectively) than respondents with backgrounds in the natural sciences (12 per cent) or engineering (12 per cent).This is somewhat surprising, because social scientists appear least likely to carry out or evaluate the results of emergy analyses, which are not commonly used in the social sciences. The validity of these results are reinforced by the results of an earlier question asking respondents about their awareness of specific EGS-valuation methods. That question found that 11 per cent of respondents had heard of emergy analysis.

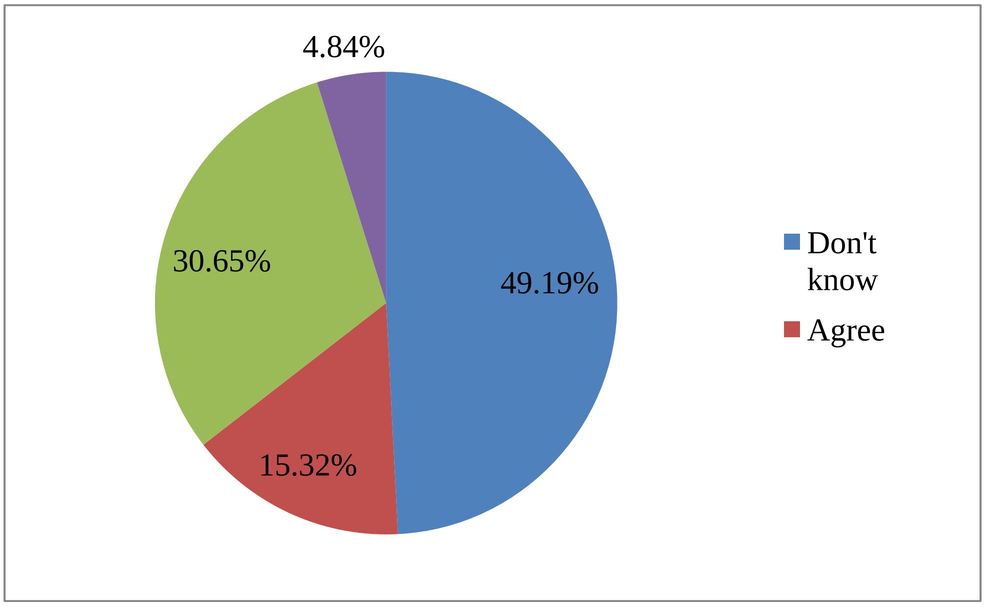
Approximately 39 per cent of respondents indicated, by selecting one or two on a six-point scale where "one" meant they strongly agreed and "six" meant they strongly disagreed, that emergy analysis could be made understandable for policy-makers. Six per cent disagreed, and a quarter of respondents did not know.

Figure 4.3 Respondents' agreement with the statement that emergy analysis can be made understandable for policy-makers.



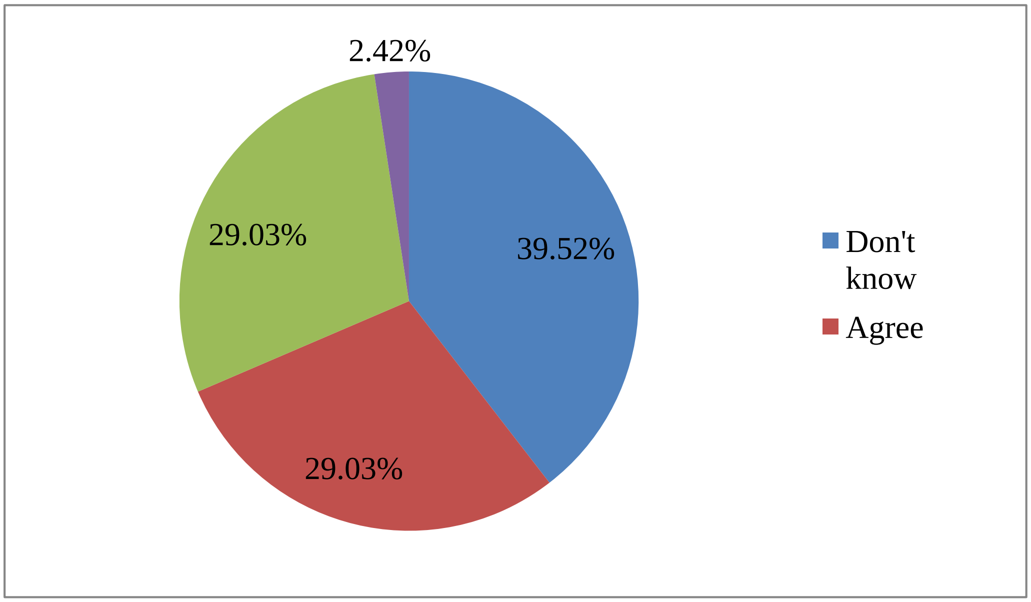
Approximately 15 per cent of respondents agreed with the statement "Emergy analysis is a difficult tool to use," while 5 per cent disagreed and 50 per cent did not know.

Figure 4.4 Respondents' agreement with the statement that emergy analysis is a difficult tool to use.



Approximately 30 per cent of respondents agreed with the statement "Emergy analysis is a useful decision-making tool," while 2 per cent disagreed and 40 per cent did not know.

Figure 4.5 Respondents' agreement with the statement that emergy analysis is a useful decision-making tool.



4.2.4 *Open-ended questions*

There was a very high response rate for the open-ended questions (73 and 77 responses, respectively, to the first and second open-ended questions). The purpose of the open-ended questions was to give respondents the opportunity to identify what they saw as strengths and weaknesses of the emergy method by asking their perspective about the usefulness of emergy analysis for decision-making and whether or not they would consider using the tool in the future. The information obtained is meant to complement the results of the previous questions.

A large proportion of the respondents indicated that they were not familiar enough with the method to determine its potential. For example, responses similar to the following statement were fairly common: "I have absolutely no idea whether or not this tool would be useful." While many respondents were positive about having a tool to value EGS, many highlighted concerns and questions that they believed could decide its usefulness.

The most common concerns related to the method's complexity and perceived difficulty of using it and communicating the results to policy-makers. Many respondents commented on the complexity of emergy analysis by making statements such as: "It is pretty complicated"; "It does seem like it would be a labour-intensive, costly process" and "It looks like it'll be hard to implement and use." With respect to the difficulty of communicating the results to policy-makers, respondents commented that "joules of energy is not an accessible concept for policy-makers" and "it seems enormously difficult to calculate or explain."

Several respondents were concerned that emergy analysis couldn't really quantify all values. This sentiment was supported by statements such as: "Cultural and spiritual values are not included"; "Emergy analyses do not say how rare the service is or how many processes rely on the service" and "Some services may be extraordinarily important but use very little solar energy." One respondent suggested that emergy analysis should be supplemented by economic valuation.

A few respondents indicated that, regardless of the value of emergy analysis, new tools were not needed. Some respondents stated that "there is plenty already out there with a more common track record which has value in the public eye" and "there are many other methods that have been used that may be less data intensive." They asked, "Why not just stick to life-cycle assessment?" as well as whether we need to make these measurements at all: "Aren't governments, business and individuals aware of [the benefits of ecosystem services]—but just slow to actually act on protecting these?" Others indicated that although the method might have value, it probably wouldn't have traction with policy-makers. One respondent stated that emergy analysis is "a bit too esoteric/intractable for many policy-makers," a concern echoed by other respondents.
Several respondents noted that all methods have weaknesses and that emergy analyses should be

used in conjunction with other valuation methods as part of an "analysis package." Quite a few respondents suggested using the analysis for "non-essentials" or as a "guideline," because they felt the method or results might not be sufficiently robust or had not yet been adequately tested, and many commented that they would like to learn more, by making statements like "I feel there is merit in analyzing what emergy can tell me" and "I would like to learn more about it."

Applications for which respondents said they would consider using emergy analysis ranged widely and included, for instance, environmental impact assessments, green design (such as green housing developments and industrial design), sectoral analyses (such as transportation and energy sectors), and measuring the baseline inputs to and outputs from national parks and protected areas versus urban and industrial areas. A couple of detailed responses provided a more in-depth critique of the method, and there were many informative comments that are not included here but are documented in Appendix D.

Table 4.1 Number of people who would consider using emergy analysis in the future.

Yes	27
No	10
Maybe	18
N/A	7
Don't know	13

The final two questions were very general and were intended to be used to identify sampling biases by separating results based on perspectives on the market economy and the state of the environment. The majority of respondents (98 per cent) felt that the value of goods and services accessed through markets is not representative of their true value and cost, and 99 per cent felt that our natural environment is threatened by human expansion and activities. The bias in the results is likely due to the fact that the target groups consist primarily of students and graduates of sustainable development and environmental and natural resource management programs.

4.3 Summary

We obtained a good number of responses (119 respondents completed the survey) and the quantity and quality of responses to the open-ended questions added significantly to the value of the survey results. A summary of the variables tested and the survey results follows:

- *Has the target group heard of emergy analysis?* Ten to fifteen per cent of respondents were familiar with emergy analysis.
- *Has the target group heard of other methods for valuing EGS?* Roughly two-thirds of respondents were familiar with EGS valuation methods.
- *Does the target group see value in using emergy as a decision-making tool?* Fifty per cent said that they considered emergy analysis to be a useful decision-making tool, 40 per cent said they did not know and 10 per cent did not consider it useful.
- *Does the target group believe that approaches for decision-making ought to be based more on biophysical measures?* More than 60 per cent agreed that approaches to decision-making ought to be more based on biophysical measures.

Two questions gauged the general position of respondents with respect to the importance of the environment. The responses indicated a strong bias toward protection of the environment and were aligned with the fact that the target groups consisted primarily of students and graduates of sustainable development and environmental and natural resource management programs. This needs to be kept in mind when reviewing the online survey results. A complete list of survey questions and responses can be found in Appendix D.

5.0 Conclusions and recommendations

The results of this study indicate that although the emergy approach may have merit for valuing EGS to support decision-making, its potential uptake within the policy-making realm could be limited because of its complexity and because of methodological criticisms within academia. Nevertheless, the emergy approach continues to evolve, and its application continues to broaden, which may lead to a wider acceptance with time.

The ubiquitous appeal of the emergy approach to measure the sustainability of systems is met by much skepticism from economists, ecologists and energy analysts, who have published their views on the limitations of the approach. Nevertheless, emergy proponents continue to advance and apply the concept within academia and public agencies in a number of different areas, such as regional development, agriculture, and natural resources management and restoration.

Separate interviews with six academic experts who had published in relevant fields revealed polarized views on the emergy approach. Emergy opponents criticized the rigour of the method, while emergy proponents viewed the approach as useful and the only way to adequately value EGS. Both groups agreed that the general objective of the approach was worthwhile and that its development has led to interesting insights, such as the notion of energy quality. They also agreed that using energetic and economic valuation methods to assess EGS would be insightful for policy-makers. Nevertheless, the conceptual and methodological complexities of the emergy approach have prevented it from being widely disseminated within the policy-making realm.

The online survey aimed to gauge the impressions of students in the Engineering and Society program and of environmental and natural resource management students and practitioners with respect to using emergy as a potential EGS valuation and decision-making tool. Alumni communities from six educational institutions and internship programs were targeted, and 119 people completed the survey. In general the respondents found that the emergy approach was an interesting method that had potential to inform decision-making. For these reasons, they deemed further looking into the emergy method worthwhile. It must be noted that all respondents had environmental and sustainable development educational experiences, which likely influenced the results obtained. People with different educational backgrounds may have answered the survey differently.

Stemming from this research, we propose two sets of recommendations for Alberta Environment. The first set of recommendations relates to further investigating the potential for using emergy as an EGS-valuation method. The second relates to broadening this study to investigate the use of other energy-based EGS-valuation methods.
Despite its methodological reservations within academia and the relatively small number of emergy

practitioners, the emergy approach continues to be developed and applied to value EGS. As it continues to progress, it may become more widely accepted by people who currently oppose it. To continue investigating the potential for applying the emergy approach to value EGS, IISD specifically recommends the following:

- Examine in more detail the methods and conventions used to conduct emergy analysis and derive solar transformity coefficients. This would enable Alberta Environment to determine its comfort level related to applying the concept.
- Apply the emergy approach, along with economic instruments, to a study area where an EGS assessment is underway or has been completed. This would familiarize Alberta Environment with the benefits and limitations of the emergy approach and would also allow for comparing valuation results from the emergy and economic analyses.
- Organize a workshop among academic experts and policy-makers to discuss approaches for valuing EGS that are either economically or energy based (which would include the emergy approach). This could yield interesting insights into how EGS values could best be derived and applied. The discussion could be framed by the U.S. EPA's EGS-valuation best practices report, which will be released shortly.

In general, adopting energy-based valuation methods alongside economically based ones to assess EGS could provide valuable insights for policy- and decision-makers and would lead to a "no regrets" situation for Alberta Environment. This viewpoint is in keeping with the soon-to-be-released U.S. EPA report on best practices for valuing EGS, which includes net-energy accounting in its suite of valuation methods. Specifically, IISD recommends the following:

- Expand this study to assess the potential for other energy-based methods, such as net-energy accounting, ecological footprint and net primary production, in valuing EGS.
- Examine the potential for using energy-based valuation methods to assess supporting ecosystem services that cannot be adequately evaluated using economic instruments. This effort would specifically focus on examining the suitability of energy-based methods to assess supporting services and avoid double counting.
- Identify the metrics that Alberta Environment and other Alberta government departments use for decision-making, to better understand how EGS-valuation information can be compatible and informative. This assessment would provide insights into the type of information the various Alberta government agencies require so that appropriate EGS-valuation (energy based or economically based) methodologies can be derived and used.

In general our study showed that there is a need for more biophysically grounded EGS-valuation methods to be incorporated within policy-making. In accordance with the saying "We can only manage what we measure," the answer may be to use a combination of biophysical and economic methods to adequately value EGS. More detailed research on the emergy methodology is needed to determine whether it should be more widely used to value EGS.

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Figure 2.10 reprinted from *Ecological Engineering,* Vol. 27, Hong-Fang Lu, Daniel E. Campbell, Zhi-An Li and Hai Ren, "Emergy synthesis of an agro-forest restoration system in lower subtropical China," pp. 175–192, Copyright (2010), with permission from Elsevier.

Appendix A Ecosystem services and valuation approaches

The Millennium Ecosystem Assessment (2003) organizes ecosystem services by grouping them into four categories: provisioning services include the basic necessities we consume and require for our survival and well-being, regulating services provide us with a habitable environment, cultural services benefit people in a non-material manner and supporting services are necessary for the continuation of the other three types of ecosystem services

Valuation methods can be organized into revealed and stated preferences methods. Revealed methods use data on actual behaviour and consumption patterns, while stated preference methods rely on responses to queries to estimate the willingness to pay for goods and services. The values of environmental assets traded in existing markets are determined by market prices driven by supply and demand and production costs. The productivity method is used to evaluate environmental quality impacts on a good's production costs. For example, water purification costs are compared with the cost of eliminating agricultural runoff. Revealed and stated preference methods within surrogate and hypothetical markets are used to capture values of ecosystem services that are not market traded. The hedonic price method is used to determine the value of environmental assets via market-traded goods. For instance, houses in quiet or non-polluted environments are in more demand. The travel cost method determines the value of environmental assets via travel expenditures for recreation. Defensive expenditures are estimated by evaluating the cost of avoiding damages as a result of adverse environmental impacts, such as air pollution or flooding, by maintaining or restoring environmental assets.

The contingent valuation method uses willingness to pay (WTP) questions about hypothetical situations to determine the value of natural capital and ecosystem services. It is the most widely used method for estimating non-use values. For example, people might be asked their WTP for better air quality, biodiversity or aesthetically pleasing landscapes. The information collected using the contingent valuation method can easily be questioned, as it consists of stated preferences based on hypothetical situations. Choice experiments involve ranking and scoring selected ecosystem services and their estimated values, allowing the analysis of preferred environmental policy options. Comparing and ranking natural environment restoration programs that lead to different outcomes is an example of a choice experiment.

Appendix B Literature review documents

Background

Odum, H. T. (1996). *Environmental accounting: EMERGY and environmental decision making*. New York: Wiley.

- This is the reference book for environmental accounting using the emergy approach.

Odum, H. T., & Odum, E. P. (2000). The energetic basis for valuation of ecosystem services. *Ecosystems, 3*, 21–23.

- This article discusses in general terms the potential for valuing ecosystem services by using emergy.

Brown, M. T., & Ulgiati, S. (2004). Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. *Ecological Modelling,* 178, 201–213.

- This article presents "a brief historical overview of the development of the concepts and theories of energy quality, and net energy that were the precursors to emergy" and describes the development of the concepts of emergy and transformity.

Hammond, G. (2007). Energy and sustainability in a complex world: Reflections on the ideas of Howard T. Odum. *International Journal of Energy Research,* 31, 1105–1130.

- Odum's ideas are critically assessed from outside his own circle in terms of insights gleaned from the use of engineering thermodynamics (energy and exergy analysis) and environmental appraisal methods, as well as those provided by the modern paradigm of "sustainability."

Brown, M. T., &. Ulgiati, S. (1999). Emergy evaluation of the biosphere and natural capital. *AMBIO, 28*(6), 486–493.

- A donor system of value based on emergy is suggested as the only means of reversing the logic trap inherent in economic valuation, which suggests that value stems only from utilization by humans. The stocks of natural capital and flows of environmental resources are evaluated in emergy and related to global world product. Several emergy indexes are introduced as a means of evaluating sustainability of economies and processes.

Ulgiati, S., & Brown, M. T. (2009). Emergy and ecosystem complexity. *Communications in Nonlinear Science and Numerical Simulation, 14*(1), 310–321.

- "Ecosystem complexity is discussed in this paper in relation to changes in structure, organization and functional capacity, as explained by changes in emergy, empower, and transformity."

Hau, J. L., & Bakshi, B. R. (2004). Promise and problems of emergy analysis. *Ecological Modelling, 178*(1–2), 215–225.

- Hau and Bakshi discuss "the main features and criticisms of emergy and provides insight into the relationship between emergy and concepts from engineering and thermodynamics, such as exergy and cumulative exergy consumption." The paper aims to clarify misconceptions and suggest solutions to problems.

Herendeen, R. A. (2004). Energy analysis and EMERGY analysis—a comparison. *Ecological Modelling, 178*(1–2), 227–237.

- This paper examines the differences between energy and emergy analysis and their strengths and weaknesses.

Cleveland, C. J., Kaufmann, R. K., & Stern, D. I. (2000). Aggregation and the role of energy in the economy. *Ecological Economics, 32*(2), 301–317.

- This paper examines various approaches to aggregating energy flows to investigate the role of energy in the economy.

Giannetti, B. F., Barrella, F. A., & Almeida, C. M. V. B. (2006). A combined tool for environmental scientists and decision-makers: Ternary diagrams and emergy accounting. *Journal of Cleaner Production, 14*(2), 201–210.

- Gianetti et al. discuss the use of ternary diagrams as "graphic tools to assist environmental accounting and environmental decision-making based on emergy analysis."

Almeida, C. M. V. B., Barrella, F. A., & Giannetti, B. F. (2007). Emergetic ternary diagrams: Five examples for application in environmental accounting for decision-making. *Journal of Cleaner Production, 15*(1), 63–74.

- This paper tests the versatility of ternary diagrams for assisting in performing emergy analyses using five example cases taken from the literature. The authors find that ternary diagrams can assist in the recognition and evaluation of details and that they provide a tool for "transparent presentation of the results" that can "serve as an interface between emergy scientists and decision makers."

Hau, J. L., & Bakshi, B. R. (2004). Expanding exergy analysis to account for ecosystem products and services. *Environmental Science and Technology, 38,* 3768–3777.

- This paper "expands the engineering concept of Cumulative Exergy Consumption (CEC) analysis to include the contribution of ecosystems, which leads to the concept of Ecological Cumulative Exergy Consumption (ECEC)."

Bakshi, B. R. (2002). A thermodynamic framework for ecologically conscious process systems engineering. *Computers & Chemical Engineering, 26*(2), 269–282.

- Various methods to adequately account for environmental impacts and ecological inputs are examined. The author states that emergy and exergy analysis can provide insight into the environmental performance and sustainability of the industrial process or product.

Tilley, D. R. (2006). *Emergy-based environmental accounting of ecosystem services in rural and urban areas.* Working paper 2006-1. College Park, MD: University of Maryland, Department of Environmental Science and Technology.

- Emergy-based environmental accounting can be used to assess the environmental values of natural environments and maximize ecological return on investment.

Applications

Lu, H.-F., Campbell, D. E., Li, Z.-A., & Ren, H. (2006). Emergy synthesis of an agro-forest restoration system in lower subtropical China. *Ecological Engineering, 27*(3), 175–192.

- Aims to increase our understanding of the structural and functional attributes of an agro-forest restoration system in China so as to be able to further optimize the system. Uses emergy indexes to evaluate the ecological and economic benefits of the restoration.

Brown, M. T., & Campbell, E. (2007). *Evaluation of natural capital and environmental services of U.S. national forests using emergy synthesis.* Gainesville, Florida: Center for Environmental Policy, University of Florida.

- The natural capital and environmental services for all national forests in the United States are assessed using an emergy synthesis. The total budget allocation for the U.S. Forest Service is compared with the environmental services, natural capital extracted, endangered species, biodiversity and genetic resources provided and found in the U.S. national forests.

Agostinho, F., Diniz, G., Siche, R., & Ortega, E. (2008). The use of emergy assessment and the Geographical Information System in the diagnosis of small family farms in Brazil. *Ecological Modelling, 210*(1–2), 37–57.

- Agostinho et al. examine the emergy of different land uses: ecological agriculture versus conventional chemical agriculture. The study incorporates GIS and the Universal Soil Loss Equation to calculate the soil loss on the farms. The agroecological model was found to be more sustainable.

Higgins, J. B. (2003). Emergy analysis of the Oak Openings region. *Ecological Engineering, 21*(1), 75–109.

- Explains emergy analysis and illustrates the method (as an alternative to market valuation) using a case study of the Oak Openings region in northwest Ohio.

Pizzigallo, A. C. I., Niccolucci, V., Caldana, A., Guglielmi, M., & Marchettini, N. (2007). Eco-dynamics of territorial systems: An emergy evaluation through time. *WIT Transactions on the Ecology and the Environment, 106*, 145–153.

- Emergy evaluation is used to analyze the sustainability of the developments in the Province of Modena, in northern Italy. This provides an example of a time-series emergy evaluation.

Chen, G. Q., Jiang, M. M., Chen, B., Yang, Z. F., & Lin, C. (2006). Emergy analysis of Chinese agriculture. *Agriculture, Ecosystems & Environment, 115*(1–4), 161–173.

- This paper provides an analysis of Chinese agriculture between 1980 and 2000 using emergy and provides background on the emergy concept. The results show the decreasing sustainability of Chinese agriculture as it moves from traditional methods toward methods that are based on consumption of non-renewable resources.

Ortega, E., Anami, M. H., & Beskow, P. R. (2005). Brazilian soybean production: Emergy analysis with an expanded scope. *Bulletin of Science, Technology & Society, 25*(4), 323–334.

- This study provides a good example of how an emergy analysis can inform public policy development. Four different soybean cultivation methods in Brazil are evaluated using an emergy approach.

Appendix C Transformity values

All information in this appendix was reprinted directly from Odum et al. (2000).

Table 9.1 Annual emergy contributions to global processes (excluding non-renewable resources).

Note	Inputs & units	Inflow units/yr	Emergy/unit sej/unit	Empower E24 sej/yr
1	Solar insolation, J	3.93 E24	1.0	3.93
2	Deep earth heat, J	6.72 E20	1.20 E4	8.06
3	Tidal energy, J	0.52 E20	7.39 E4	3.83
	Total	-	-	15.83

Abbreviations: sej = solar emjoules; yr = year; E3 means multiplied by 10^3

1. Sunlight: solar constant 2 gcal/cm2/min = 2 Langley per minute; 70% absorbed; earth cross-section facing sun 1.27 E14 m2.
2. Heat release by crustal radioactivity 1.98 E20 J/yr plus 4.74 E20 J/yr heat flowing up from the mantle (Sclater et al., 1980). Solar transformity 1.2 E4 sej/J is from Folio #2 based on an emergy equation for crustal heat as the sum of emergy from earth heat, solar input to earth cycles, and tide.
3. Tidal contribution to oceanic geopotential flux is 0.52 E20 J/yr. Solar transformity 7.4 E4 sej/J from Folio #2 following Campbell (1998) is based on an emergy equation for oceanic geopotential as the sum of emergy from earth heat, solar input to the ocean, and tide.

Table 9.2 Emergy products of the global energy system.

Note	Inputs & units	Emergy* E24 sej/yr	Production units/yr	Emergy/unit sej/unit
1	Global latent heat, J	15.83 E24	1.26 E24	12.6 sej/J
2	Global wind circulation, J	15.83 E24	6.45 E21	2.45 E3 sej/J
3	Global precipitation on land, g	15.83 E24	1.09 E20	1.45 E5 sej/g
4	Global precipitation on land, J	15.83 E24	5.19 E20	3.1 E4 sej/J
5	Average river flow, g	15.83 E24	3.96E 19	4.0 E5 sej/J
6	Average river geopotential, J	15.83 E24	3.40 E20	4.7 E4 sej/J
7	Average river chemistry. energy, J	15.83 E24	1.96 E20	8.1 E4 sej/J
8	Average waves at the shore, J	15.83 E24	3.10 E20	5.1 E4 sej/J
9	Average ocean current, J	15.83 E24	8.60 E17	1.84 E7 sej/J

* Main empower of inputs to the geobiospheric system from Table 9.2 not including non-renewable consumption (fossil fuel and mineral use).

1. Global latent heat, evapotranspiration 1020 mm/yr, (1020 mm/yr)(100 g/m2/mm)(0.58

kcal/g)(4186 J/kcal)(5.1 E14 m2) = 1.26 E24 J/yr

2. Global wind circulation, 0.4 watts/m2 (Wiin-Nielsen & Chen, 1993) (0.4 J/m2/sec) (3.15 E7 sec/yr)(5.12 E14 m2/earth) = 6.45 E21 J/yr
3. 1.09 E11 m3/yr (Ryabchikov, 1975) (1.09 E14 m3)(1 E6 kg/m3) = 1.09 E20 g/yr
4. Chemical potential energy of rain water relative to sea water salinity (1.05 E20 g/yr)(4.94 J Gibbs free energy/g) = 5.19 E20 J/yr
5. Global runoff, 39.6 E3 km3/yr (Todd, 1970) (39.6 E12 m3/yr)(1 E6 g/m3) = 3.96 E19 g/yr
6. Average river geopotential work; average elevation 875 m. (39.6 E12 m3/yr)(1000 kg/m3)(9.8 m/sec2)(875 m) = 3.4 E20 J/yr
7. Chemical potential energy of river water relative to sea water salinity (3.96 E19 g/yr)(4.94 J Gibbs free energy/g) = 1.96 E20 J/yr
8. Average wave energy reaching shores, (Kinsman, 1965) (1.68 E8 kcal/m/yr)(4.39 E8 m shore front)(4186 J/kcal) = 3.1 E20 J/yr
9. Average current: 5 cm/sec (Oort et al., 1989); 2-year turnover time (0.5)(1.37 E21 kg water)(0.050 m/sec)(0.050 m/sec)/(2 yr) = 8.56 E17 J/yr

Table 9.3 Annual emergy contributions to global processes including use of resource reserves.*

Note	Inputs & units	Inflow J/yr	Emergy/unit# sej/unit	Empower E24 sej/yr
1	Renewable inputs	-	-	9.44
Non-renewable energies released by society				
2	Oil, J	1.38 E20	5.40 E4	7.45
3	Natural gas, (oil eq.), J	7.89 E19	4.80 E4	3.79
4	Coal (oil eq.), J	1.09 E20	4.00 E4	4.36
5	Nuclear power, J	8.60 E18	2.00 E5	1.72
6	Wood, J	5.86 E19	1.10 E4	0.64
7	Soil, J	1.38 E19	7.40 E4	1.02
8	Phosphate, J	4.77 E16	7.70 E6	0.37
9	Limestone, J	7.33 E16	1.62 E6	0.12
10	Metal ores, g	993 E12g	1.0 E9 sej/g	0.99
Total non-renewable empower		-	-	20.46
Total global empower		-	-	29.90

Abbreviations: sej = solar emjoules; yr = year; E3 means multiplied by 103; t = metric ton; oil eq. = oil equivalents
* Modified from Brown and Ulgiati (2000) using global base 9.44 E24 sej/yr
# Values of solar emergy/unit from Odum (1996)

1. Renewable inputs: Total of solar, tidal, and deep heat empower inputs from Odum (1996)

2. Total oil production = 3.3 E9 Mt oil equivalent (British Petroleum, 1997)
   Energy flux = (3.3 E9 t oil eq.)(4.186 E10 J/t oil eq.) = 1.38 E20 J/yr oil equivalent
3. Total natural gas production = 2.093 E9 m3 (British Petroleum, 1997)
   Energy flux = (2.093 E12 m3)(3.77 E7 J m3) = 7.89 E19 J/yr
4. Total soft coal production = 1.224 E9 t/yr (British Petroleum, 1997)
   Total hard coal production = 3.297 E9 t/yr (British Petroleum, 1997)
   Energy flux = (1.224 E9 t/yr)(13.9 E9 J/t) + (3.297 E9 t/yr)(27.9 E9 J/t) = 1.09 E20 J/yr
5. Total nuclear power production = 2.39 E12 kwh/yr (British Petroleum, 1997).
   Energy flux = (2.39 E12 kwh/yr)(3.6 E6 J/kwh) = 8.6 E18 J/yr electrical equivalent
6. Annual net loss of forest area = 11.27 E6 ha/yr (Brown et al., 1997)
   Biomass = 40 kg m2; 30% moisture (Lieth and Whitaker, 1975)
   Energy flux = (11.27 E6 ha/yr)(1 E4 m2/ha)(40 kg m2)(1.3 E7 J/kg)(0.7) = 5.86 E19 J/yr
7. Total soil erosion = 6.1 E10 t/yr (Oldeman, 1994; Mannion, 1995)
   Assume soil loss 10 t/ha/yr and 6.1 E9 ha agricultural land = 6.1 E16/g/yr
   (assume 1.0% organic matter), 5.4 kcal/g
   Energy flux = (6.1 E16 g)(.01)(5.4 kcal/g)(4186 J/kcal) = 1.38 E19 J/yr
8. Total global phosphate production = 137 E6 t/yr (USDI, 1996)
   Gibbs free energy of phosphate rock = 3.48 E2 J/g
   Energy flux = (137 E12 g)(3.48 E2 J/g) = 4.77 E16 J/yr
9. Total limestone production = 120 E6 t/yr (USDI, 1996)
   Gibbs free energy phosphate rock = 611 J/g
   Energy flux = (120 E12 g)(6.11 E2 J/g) = 7.33 E16 J/yr
10. Total global production of metals 1994: Al, Cu, Pb, Fe, Zn (World Resources Institute, 1996): 992.9 E6 t/yr = 992.9 E12 g/yr

Appendix D Expert interviews

Interviewees:

Proponents

Mark Brown. Mark Brown is an associate professor in environmental engineering sciences and directs a program in systems ecology and ecological engineering at the University of Florida. He was appointed director of the Center for Environmental Policy in the spring of 2006. Dr. Brown is a protege of H.T. Odum and big proponent of emergy analysis.

Dan Campbell. Dan Campbell works for the U.S. EPA's Office of Research and Development, in their National Health and Environmental Effects Research Laboratory in Narragansett, Rhode Island. He has been involved with publishing and working on various aspects of applying emergy for planning.

David Tilley. David Tilley is an associate professor with the Natural Resource Management Program in the Department of Environmental Science and Technology at the University of Maryland. His research interests include ecological engineering design, net-energy analysis, environmental accounting of ecosystem services, emergy analysis and industrial ecology.

Opponents

Robert Costanza. Robert Costanza is a professor of ecological economics and director of the Gund Institute for Ecological Economics at the University of Vermont. Dr. Costanza worked closely with energy-based measurement to value EGS, but eventually focused on economic instruments to estimate EGS values.

Geoffrey P. Hammond. Geoffrey Hammond is a professor of mechanical engineering and director of the interdisciplinary International Centre for the Environment at the University of Bath. He is a mechanical engineer with a multidisciplinary background, including environmental engineering and management.

Robert Herendeen. Robert Herendeen is a professional scientist at the Illinois Natural History Survey in Urbana-Champaign. He is an associate professor in the Department of Animal Biology and Department of Urban and Regional Planning. He is also an adjunct professor of natural resources and environmental studies. His research interests include indicators of environmental impact and sustainability, particularly of agricultural systems; trophic cascades and dynamics of perturbed food webs; theoretical ecology; the connection between economics and ecology; modelling growth and survival of fish populations; and use of energy in natural and human systems.

Semi-structured questionnaire:

Questions centred around three themes: scientific robustness, policy relevance and next steps for Alberta Environment. They addressed the following questions:

- What is the scientific robustness and ease of conducting an emergy analysis?
- What is the potential for emergy to be used as a policy/decision-making tool?
- Do they think emergy analysis meets the criteria of a good decision-making tool?
- Do they think that it is better for valuing non-market-traded ecosystem services than other available tools?

Variables to test

- Validity
- Availability and timeliness of data
- Reliability and stability
- Responsiveness
- Understandability
- Policy relevance
- Representativeness

Introduction

I am planning on recording this conversation. Is that okay with you? Your permission will first be sought if any of your thoughts will be used in the final report.

Please give me some examples of your work related to emergy or energy analysis.

How long have you worked in this field, and what attracted you to this area of research?

Science

- How would you characterize the degree of difficulty/ease in conducting emergy analyses?
- How would you characterize the degree of difficulty/ease in conducting emergy analyses relative to other tools for valuing non-market-traded goods and services?
- How would you describe the degree of responsiveness of emergy analysis to changes in the environment (for instance climate change)?
- How would you assess the validity of emergy analysis as a tool for measuring the value of non-market-traded goods and services?
- How well do you think the results of emergy analyses can represent the true value of goods and services?
- How probable do you think it would be that the data required for emergy analyses of non-

market-traded goods and services be available?

- How would you describe emergy analysis in terms of objectivity/subjectivity relative to other tools for valuing non-market-traded goods and services?
- Are you aware of any other tools that could be used for valuing non-market-traded goods and services?
- Would you consider using emergy analysis in the future? If yes, for what applications? If no, why not?

Policy

- How understandable do you think the results of emergy analysis could be made for policy-makers?
- How would you describe the degree of subjectivity/objectivity of emergy analyses?
- How would you rate the relevance of the results of emergy analysis for the purpose of policy-making?
- How understandable do you think the results of emergy analyses would be relative to other tools for valuing non-market-traded goods and services?
- How would you rate the degree of difficulty/ease in conducting emergy analyses relative to other tools for valuing non-market-traded goods and services?

General

- Do you feel that the value of goods and services that we access through the markets are representative of their true value and cost?
- How would you rate your knowledge of methods to value non-market-traded goods and services? Is this knowledge something that you might find useful in the future?
- Give us your general impression of whether emergy analysis has merit to value ecosystem services and assist with decision- and policy-making.

Appendix E Online survey

Table 11.1 What is your age?

Answer options	Response frequency (%)	Response count
18–25	32.1	44
26–30	21.2	29
31–35	23.4	32
Older than 35	23.4	32
	answered question	137
	skipped question	0

Table 11.2 Gender.

Answer options	Response frequency (%)	Response count
Male	48.2	66
Female	51.8	71
	answered question	137
	skipped question	0

Table 11.3 Educational background.

Answer options	Response frequency (%)	Response count
Other	3.6	5
Natural sciences	43.8	60
Social sciences	31.4	43
Management	20.4	28
Engineering	43.8	60
Other (please specify)		21
Other (please specify)		
Health sciences		
Ecological economics		
Masters of environmental studies		
Environmental studies		
Cultural studies, urban planning		
Environment		
Also GIS		
Theatre and film studies		

History
Arts and education
Veterinary medicine
Public policy
Law
Landscape architecture
Planning
Environmental management
Interdisciplinary studies
Natural resources management
Resource management
Communications
Music minor

Table 11.4 Post-secondary institutions and programs attended.

Number	Response Text
1	Masters Environmental Management
2	Masters in Environmental Management candidate
3	University of Manitoba BSc Environmental Science Royal Roads University Masters in Environment and Management (in progress)
4	University of Victoria, B.Sc. Human Performance, Co-op Royal Roads University, MA, Environment and Management (2008 Cohort)
5	UBC, Vancouver, BC RRU, Victoria, BC
6	- University of Alberta - British Columbia Institute of Technology - Royal Roads University
7	University of Manitoba – NRI
8	U of Manitoba – Master of Natural Resources Management U of Toronto – B.Sc.
9	University of Guelph, B.Sc. Env (Natural Resources Management); Niagara College – Post Graduate Certificate in Environmental Management & Assessment
10	University of Manitoba
11	University of Toronto – Chemical Engineering (BASc) Royal Roads University – Masters of Environmental Management (MSc)
12	Environmental Technology Diploma, College of the North Atlantic, Bachelor of Engineering Technology, Environmental studies, Cape Breton University, Master of Science, Environment and Management, Royal Roads University.
13	Carleton University Royal Roads
14	Thompson Rivers University (BA–Geography) University of Guelph (MA–Geograhpy)
15	University of Regina Simon Fraser University
16	Natural Resources Institute, Manitoba

17	NAIT – Biological Sciences – Renewable Resources UNBC – BSc. in Wildlife and Fisheries Management RRU – Masters in Environment and Management
18	UofM
19	Royal Roads University
20	University of Victoria – BSc. Biology/Environmental Studies Dalhousie University – Masters Environmental Studies Dalhousie University – Interdisciplinary PhD (Ecological Economics, in progress)
21	BA International Development, University of Guelph Masters Environmental Studies, Dalhousie
22	Dalhousie – Master of Environmental Studies UBC – Bachelor of Science (Ecology & Envmt Biology)
23	British Columbia Institute of Technology – Environmental Engineering British Columbia Institute of Technology – Renewable Resources
24	RRU Masters of Environment and Management
25	Queen's University – B.Sc.Hons in Biology Dalhousie University – Master of Environmental Studies
26	School of Resource and Environmental Studies, University of Dalhousie
27	Mount Royal College, Environmental Technology Diploma; Mount Royal College, Bachelor of Applied Industrial Ecology; RRU, Environment and Management
28	trent university, dalhousie university
29	Dalhousie University, BSc. Environmental Science, emphasis in ecology and MES (Master of Environmental Studies).
30	Honours B.A. (Geography) – University of Western Ontario Master of Environmental Studies – Dalhousie University
31	queen's university; university of manitoba (NRI)
32	Mount Allison University: BA Geography Dalhousie University: Master of Environmental Studies
33	UBC – Geography (human and environmental) and English BCIT – (Post grad) Advanced Diploma in Geographic Information Systems.
34	SFU, BSc. in Environmental Science
35	McGill University, Wildlife Biology/Psych Dalhousie University, Environmental management/Business/sociology
36	1. Dalhousie University, Master of Environmental Studies; 2. Saint Mary's University, Bachelor of Science; 3. Saint Mary's University, Bachelor of Arts; 4. DalTech Continuing Education, ISO 14000 Auditor Accreditation
37	(1) Master in Environmental Studies – Dalhousie University, Canada (2) BSc Hons in Forestry – Chittagong University, Bangladesh
38	University of Leeds BEng Mechanical engineering MA Sustainable Development PhD environmental social sciences
39	McMaster University Engineering Physics – Bachelor of Engineering and Society, Master of Applied Science
40	McMaster
41	Engineering Physics & Society

	McMaster University
42	N/A
43	McMaster University Chemical Engineering and Society
44	McMaster – B.ENG. Civil & Society Queen's – Masters of Urban and Regional Planning (2009)
45	McMaster – Materials Engineering and Society (Minor in Theatre and Film)
46	McMaster University: Engineering and Society (Materials)
47	McMaster Civil Engineering and Society (BEng) Concordia University Building Engineering (MASc)
48	Lakehead University – HBScForestry Dalhousie University – MES
49	Civil Engineering and Society at McMaster Masters of Public Policy and Administration at Carleton
50	McMaster University – Software and Society McMaster University – English (BA) Western – Education (B. Ed.)
51	Civil (Environmental) Engineering and Society McMaster University
52	mcmaster eng & society
53	McMaster, Engineering Physics
54	McMaster Engineering
55	McMaster University – Civil Engineering
56	McMaster, Civil Eningeering
57	McMaster University Engineering
58	McMaster University, B.Eng.Soc.
59	McMaster University Engineering Physics and Society
60	McMaster – B.Eng & M.Eng.
61	Mechanical Engineering and Society at McMaster University
62	McMaster University, Engineering & Society program
63	STFX, NSAC, DALHOUSIE
64	U of M; NRI
65	McMaster Civil Engineering and Society York University Earth and Space Sciences (MSc)
66	McMaster University – Civil Engineering
67	McMaster University – Chemical Engineering And Society
68	Land Use and Environmental Studies with a major in Economics from the University of Saskatchewan
69	McMaster University, Civil (Environmental) Engineering and Society
70	McMaster University – Bachelor of Mechanical Engineering & Society McMaster University -–Masters of Applied Science
71	McMaster University
72	McMaster University, Civil Engineering and Society
73	McMaster
74	McMaster University, Chemical Engineering and Society
75	University
76	Dalhousie University – School for Resource and Environmental Studies

77	Selkirk College Wildland Recreation Diploma UVIC – BSc in Biology and Geography Royal Roads – Environment and Management
78	McMaster University: Civil Engineering
79	Sheridan College – Corporate Communications
80	Queen's University: Applied Science, Geology Ridgetown College University of Guelph: Veterinary Technology McMaster University: Engineering
81	FLACSO-Ecuador, Local and Territorial Development
82	Master's in Resource and Environmental Management
83	Dalhousie University, BA – International Development and Economics
84	McMaster University
85	University of Victoria – Geography Concordia University – Geography (BA) University of BC – Resource Mngmt and Env.Studies (MSc)
86	McMaster – Mechanical Engineering and Society UofT – Master of Applied Science in Mechanical Engineering
87	McMaster University: Mechanical Engineering & Society Masters of Engineering & Public Policy
88	Carleton University, University of Guelph
89	University of Manitoba: B.B.A University of Waterloo: MES/ERS
90	Universidad Iberoamericana Royal Roads University
91	Université Laval – International development Royal Roads University – Intercultural communication
92	Alberta College of Art and Design – Bachelor of Fine Arts University of Alberta – Law
93	McGill – B.Sc Environment Simon Fraser University – Masters of Resource and Environmental Management
94	Queen's University, BSc Chemistry Simon Fraser University– Master of Resource Management
95	McMaster University
96	McMaster, Engineering York University, MBA
97	University of Manitoba Agriculture Royal Roads University Master of Science Candidate
98	Vancouver Island University – BA (Geography, Anthropology) Simon Fraser University – Master's in Resource Management
99	MEM Royal Roads
100	SFU REM SFU MA Econ UVIC BA Econ
101	McMaster University Engineering and Society, Civil.
102	Dalhousie University University of Victoria
103	University of Victoria.

	Gulf Islands Film & Television School.
104	University of Waterloo University of Alberta Trent University
105	Tourism Management (BTM) Thompson Rivers University Resource Management (MRM) Simon Fraser University
106	UVic BSc Geography SFU MRM resource management SFU PhD resource management (currently)
107	McMaster University
108	SFU – REM U of T – pharmacology
109	mcmaster university
110	SFU: Resource and Environmental Management SFU: Sustainable Community Development
111	RRU – MEM Program
112	UWO: BA (English and Philosophy) McGill: Diploma in Environmental Studies University of London (UK): MSc in Public Understanding of Environmental Change (Geography)
113	University of Calgary, B.Sc Geography University of Calgary, M.Sc. Resources and the Environment
114	University of Toronto, Environmental Science McGill University, Renewable Resources
115	SFU School of Resource and Environmental Management
116	McGill University – BSc in Biology University of Manitoba – MSc Botany
117	Master's of Natural Resource Management – University of Manitoba Bachelor's of Zoology – University of Manitoba
118	University of Alberta, Science University of Calgary, Management
119	master Environmental Sciences
120	Chemical Engineering and Society at McMaster University
121	School of research and environmental studies
122	1979–1984, University Autonomous of Sinaloa. Faculty of Marine Sciences. Bachelor Program "Fisheries Biologist"; 1987–1990, CINVESTAV-Mérida, Mexico. Program of "Master of Science in Marine Biology", Mexico; 2001–2007. Dalhousie University. Interdisciplinary PhD, Programme, Canada.
123	U of Manitoba – Natural Resources Institute
124	Lakeland College, School of Environmental Sciences. Diploma in Environmental Conservation and Reclamation. Applied degree in Environmental Management.
125	McMaster University
126	McMaster University (undergraduate) University of Toronto (graduate)
127	Thompson Rivers University – Adventure Tourism Diploma and Bachelor of Tourism Management; Simon Fraser University – Master of Resource Management (Planning)
128	University of Ottawa
129	UBC – Geological Engineering (BASc) SFU – Resource and Environmental Management (MRM)

130	McMaster Eng Phys & Society
131	Mcmaster university chemical engineering and society
132	Queen's University, Geography and Developmental Studies
133	University of Ottawa, Communication BA University of Oxford, MSc Environmental Change and Management
134	McMaster – Mechanical Engineer & Society McMaster – Mechanical Masters of Applied Science Guelph – PhD
135	UBC SFU Royal Roads
136	McMaster University, Engineering Physics & Society
137	University of Winnipeg (International Development Studies – BA), Dalhousie University (Resource and Environmental Management – Master of Management)

Table 11.5 Area of residence.

Answer options	Response frequency (%)	Response count
Maritimes	3.6	5
Quebec	2.9	4
Ontario	40.1	55
Western Canada (MB, SK, AB, BC)	46.0	63
Territories	1.5	2
Outside Canada	9.5	13
	answered question	137
	skipped question	0

Table 11.6 Area of employment.

Number	Response text
1	Victoria BC
2	On leave – but have worked as an environmental advisor for the oil and gas industry, and currently work with Parks Canada
3	Analytical Chemistry
4	Self employed (tax and bookkeeping business plus organic foods business)
5	Fisheries Management
6	Environmental Public Health
7	Environmental Management
8	Water Utility Aboriginal Relations
9	Environmental Consulting
10	Natural resources management
11	Environmental Consulting

12	Industry
13	Government
14	Environmental Policy Tools
15	Government
16	Natural Resources Management – Protected Areas
17	Education
18	Conservation
19	Environmental Management
20	graduate student
21	environmental NGO
22	Municipal Government
23	Municipal Government
24	Local government
25	Government – development and analysis of environmental policy
26	United Nations
27	Government
28	eco-industrial planning
29	Student
30	Toronto, Ontario
31	resource planning
32	Student
33	Environmental planning (consulting)
34	Renewable Energy
35	Sustainable Development
36	National Capital Region
37	Forestry and Natural Resource Management
38	PhD student
39	Grad Student
40	Civil Eng
41	Medical Physics
42	Telecommunications
43	Pulp and Paper
44	Student
45	N/A
46	none at present
47	none
48	Government – Social Science Forestry Research
49	Student
50	Education
51	Water Resources
52	telecommunications
53	Student
54	Engineering
55	Most likely GTA
56	Engineering
57	Student

58	Construction
59	none
60	Engineering Consulting
61	None: Student
62	Process Engineer
63	GRAD STUDENT
64	Contract
65	Environmental planning
66	Quality Control
67	Chemical Engineering
68	Northern Parks Establishment Officer with Parks Canada
69	Environmental Consulting
70	Aerospace
71	Engineering
72	Teaching Assistant
73	none
74	Environmental Consulting
75	Student
76	BC Parks – Planner
77	Environment
78	Student
79	Public Relations
80	Student
81	Development Programs
82	Public Sector
83	Environmental Development Research
84	Student
85	Graduate student
86	Student
87	Not yet
88	Government
89	Waterloo, Ontario
90	Pharmaceutical
91	communications
92	Law
93	student
94	Energy modelling and GHG reduction policy analysis
95	Consulting
96	Manufacturing
97	Environmental Consulting
98	Student
99	city parks
100	energy
101	Structural Engineering
102	Planning
103	UN Environment Programme

104	academic
105	Teaching/Consulting
106	grad student and consultant
107	Hospitality
108	toxicology
109	snowboarding...engineering related work in the spring probably
110	Graduate Student
111	Environmental organization management, agriculture, carbon offset trading
112	Self-employed
113	Environmental Consulting
114	Environment
115	Park management
116	Government
117	Water Policy
118	consulting
119	Environment
120	geotechnical and environmental consulting firm
121	medical faculty, and also environmental study centre in Indonesia
122	Public Institution (Federal government) of research and graduate studies
123	Agriculture and Agri-Food Canada
124	Western Alberta
125	Student
126	none at the moment
127	consultant and post-secondary instructor (tourism, land use, policy and planning)
128	consulting
129	Graduate student
130	Cambridge
131	Mining
132	Intern
133	Environmental consulting
134	Marketing Manager for Global Company
135	government
136	Student currently
137	not currently employed – previously worked in environmental education & awareness building

Table 11.7 **Decision-making is largely based on biophysical measures as opposed to other (e.g., economic) measures at present.**

Answer options	Response frequency (%)	Response count
1 Strongly Agree	0.8	1
2	2.4	3
3	6.3	8
4	12.7	16
5	38.1	48
6 Strongly disagree	35.7	45
Don't know	4.0	5
	answered question	126
	skipped question	11

Table 11.8 **Tools for decision-making related to natural resource management should be more based on biophysical measures than at present.**

Answer options	Response frequency (%)	Response count
1 Strongly agree	31.0	39
2	34.9	44
3	20.6	26
4	7.1	9
5	2.4	3
6 Strongly disagree	1.6	2
Don't know	2.4	3
	answered question	126
	skipped question	11

Table 11.9 **Decision-making is largely based on economic measures as opposed to other (e.g., biophysical) measures at present.**

Answer options	Response frequency (%)	Response count
1 Strongly agree	33.3	42
2	34.9	44
3	16.7	21
4	2.4	3
5	7.9	10
6 Strongly disagree	2.4	3
Don't know	2.4	3
	answered question	126
	skipped question	11

Table 11.10 **Tools for decision-making related to natural resource management should be more based on economic measures than at present.**

Answer options	Response frequency (%)	Response count
1 Strongly agree	3.2	4
2	4.0	5
3	4.0	5
4	24.6	31
5	28.6	36
6 Strongly disagree	32.5	41
Don't know	3.2	4
	answered question	126
	skipped question	11

Table 11.11 **How would you rate your knowledge of methods to value ecosystem goods and services?**

Answer options	Response frequency (%)	Response count
1 Very knowledgeable	10.4	13
2	22.4	28
3	27.2	34
4	19.2	24
5	16.0	20
6 No knowledge	4.8	6
	answered question	125
	skipped question	12

Table 11.12 **Are you aware of any methods for measuring the value of ecosystem goods and services?**

Answer options	Response frequency (%)	Response count
No	34.4	43
Yes	65.6	82
	answered question	125
	skipped question	12

Table 11.13 **If you answered Yes to the previous question, please select which methods of measuring the value of ecosystem goods and services you are familiar with (if any).**

Answer options	Response frequency (%)	Response count
Contingent valuation (willingness to pay surveys)	70.7	58
Choice experiments	30.5	25
Market pricing	69.5	57
Hedonic pricing	28.0	23
Emergy analysis	17.1	14
Travel costs	42.7	35
Productivity method	19.5	16
Damage cost avoided	34.1	28
Replacement costs	51.2	42
Substitute cost methods	34.1	28
Benefit transfer	24.4	20
	answered question	82
	skipped question	55

Table 11.14 **Is knowledge about methods to value ecosystem goods and services something that you might find useful in the future?**

Answer options	Response frequency (%)	Response count
Yes	96.8	121
No	3.2	4
	answered question	125
	skipped question	12

Table 11.15 **Had you previously heard of emergy (eMergy, not eNergy) analysis?**

Answer options	Response frequency (%)	Response count
Yes	13.7	17
No	86.3	107
	answered question	124
	skipped question	13

Table 11.16 **Emergy analysis can be made understandable for policy-makers.**

Answer options	Response frequency (%)	Response count
1 Strongly agree	9.7	12
2	29.0	36
3	20.2	25
4	9.7	12
5	4.8	6
6 Strongly disagree	1.6	2
Don't know	25.0	31
	answered question	124
	skipped question	13

Table 11.17 **Emergy analysis is a difficult tool to use.**

Answer options	Response frequency (%)	Response count
1 Strongly agree	1.6	2
2	13.7	17
3	21.8	27
4	8.9	11
5	4.0	5
6 Strongly disagree	0.8	1
Don't know	49.2	61
	answered question	124
	skipped question	13

Table 11.18 **Emergy analysis is a useful decision-making tool.**

Answer Options	Response frequency (%)	Response count
1 Strongly agree	5.6	7
2	23.4	29
3	21.8	27
4	7.3	9
5	0.8	1
6 Strongly disagree	1.6	2
Don't know	39.5	49
	answered question	124
	skipped question	13

Table 11.19 **Give us your general impression of whether emergy analysis has potential as a tool for determining the value of ecosystem services for decision- and policy-making.**

A potential tool, yes. However, it is very complicated and the data inputs are not necessarily always going to be available. Similarly, there may be differing opinions on several of the inputs (and their magnitudes) which could easily lead to mistrust in the system from a number of parties.
Any tool that illustrates the long term economic value of conserving functioning ecosystems is a useful tool for policy making and decisions.
Any tools will further our development in a sustainable and resilient way, especially since so few are available today and most decision makers are not using them.
Appears to be viable—would need further info.
Based on the principles of energetics (Lotka 1922, 1945), systems theory (von Bertalanffy 1968) and systems ecology (Odum 1975, 1988, 1996), emergy analysis (EMA) is a quantitative analytical technique for determining "the values of nonmonied and monied resources, services and commodities in common units of the solar energy it took to make them" (Brown and Herendeen 1996). Emergy analysis proceeds from the recognition that much of the human enterprise depends on flows of solar energy, which ultimately limit the rate at which emergy can be stored by and flow through the global economic system. In contrast to energy, emergy is not conserved. Rather, it is a measure of the energy quality of a product/service, not its quantity (Sciubba and Ulgiati 2005). The solar emergy of a resource or commodity is calculated by expressing all of the resource and energy inputs to its production in terms of their underpinning solar energy inputs (emJoules or emj). The resulting total can then be used to calculate the "transformity" for the resource or commodity, which is a ratio of the total emergy used relative to the energy produced (emj/J). Transformities have been calculated for a wide range of materials and energy sources, and are typically used to inform analyses of other product/service systems to which the materials/energy sources are themselves inputs (Brown and Herendeen 1996, Odum 2000). The use of average transformities is convenient and time-effective, but may compromise the accuracy of analyses, depending on geographical and temporal representivity. Nonetheless, this technique does provide valuable insight into the energy performance of economic activities in terms of our primary renewable resource. Of particular interest is the signals it supplies regarding current cumulative rates of non-renewable energy consumption relative to available renewable sources, which is of value to forecasting future energy scenarios (Hau and Bakshi 2004; Mayer 2008). In theory, emergy analysis can be applied to systems across scales, although in practice necessary data are unavailable for many scales and low-resolution data compromises accuracy at larger scales (Odum et al. 2000; Brown and Ulgiati 2001; Brandt-Williams 2002; Mayer 2008). To date, emergy analysis has been and is increasingly applied to evaluate a variety of systems including geographical regions (for example, see Pulselli et al. 2008; Lei et al. 2008), food production (for example, see Rotolo et al. 2007; Vassallo et al. 2007; Maud 2008) and industrial processes (for example, see Brown and McClanahan 1996; Min and Feng 2008; Pulselli et al. 2008). Critics point to the challenge of defining emergy values for many abiotic materials, and question the physical validity of the methodology (Ayres 1998; Cleveland et al. 2000; Hammond 2007). Emergy analysis is one of several useful biophysical indicators which should be used for decision- and policy making. All of these can be simultaneously executed under the umbrella of an ISO-compliant LCA framework, which allows for assessment of tradeoffs along multiple dimensions of biophysical environmental sustainability.
Complex, but balanced. Probably better tool for the big picture.
Data capture may be a major challenge. What are current applications/ Sounds like emerging theoretical tool vs. practical applied tool
do not know enough about it
Does not provide a measure of human value/preferences therefore of no real use in decision making process. Some assigned value needs to be made based on the functional value generated through an emergy analysis

Don't know
Don't know
Emergy analysis seems like a useful tool for valuing many types of services and resources in a common framework, but may pose problems due to the unfamiliar common measure. Solar energy is not used in other valuation methods or by people in general. This may lead to problems when asking, "What is X amount of solar energy really worth? How do I communicate that to my supervisor or other decision makers?"
Emergy analysis can estimate for us the amount of energy required in daily life (industry, households, schools, government, hospitals, health, among many others). And as most of the life in earth is dependent upon ecosystem services, we could use Emergy analysis to provide us with the real picture (estimate) of dependency (humans and other fauna and flora dependent on ecosystem services). If we emphasize the Emergy analysis in terms of efficiency and energy saving to reach our goals, I think the tool is most useful, provided decision makers had a previous training (capacity building) on the basis and applications of this tool.
first I have heard of it, sounds interesting
From what I hear it would at least be interesting, and possibly informative as to how much stress we are putting on the energy webs of the environment.
How many joules of energy is not an accessible concept for policy-maker I fear. In addition, I don't know that they will give a darn about how much energy nature puts in it, as long as it does, they might not care. Sorry, I would go with other tools to make it tangible and ensure that the fear of scarcity sets in.
I agree that a tool is needed but actually calculating emergy seems very subjective.
I believe emergy analysis does have a high potential for being a useful tool to quantify the value of ecosystems for use in making decisions and policy.
I believe that defining the value of an ecosystem service can be a significant benefit when decision makers are deciding if a project is of value to people however, the implementation of such a tool will be near impossible in our lifetime.
I believe there is potential, but one barrier I can imagine is getting agreement and standardization amongst stakeholders on what the values should be. Also, my opinion is the use of a new word that is very similar to an existing word could be a barrier to getting much traction with policy makers.
I don't know enough about it to provide an informed opinion.
I feel that emergy could be used as relative guide to energy input to ecosystem services. However to use it as an all encompassing gauge for the worth of an ecosystem service in terms of energy would be folly. There could be vital ecosystem services which have a very small amount of emergy associated with them and could be written off as relatively unimportant.
I feel this tool would be extremely well suited for agricultural and natural areas that are being taken over by urban expansions. I don't feel it would be easily formatted to serve in remote wilderness areas.
I haven't heard of this technique before, therefore it is difficult for me to really give an impression based only on the information presented in this survey. My evaluation of this technique is based on my experience with valuing ecosystem services using other methods and I think that there are major barriers to policy making outside of the methods used to measure services. Firstly, many conservation practioners are not supportive of economic valuation of "nature" based on ethical grounds. Secondly, it is very difficult to implement management strategies based on ecosystem service values if we do not have markets that we can use to realize the values we are talking about. If we do not have active participation in these markets we can not expect policy/decision makers to appreciate the "work that nature does." It seems (from this limited information) that emergy analysis may be a novel technique to quantify ecosystem services in a common unit—but I think that there are many other methods that have been used that may be less data intensive.
I only know about this topic from reading the definition on the previous page. It appears to be similar to the GDP as a way of quantifying our national potential or wealth in ecosystem terms. I suppose that emergy analysis could have some value and that there likely are some good uses and some misuses associated with

the calculations.
I see some potential for its use as a decision-making tool. I am a bit concerned about the potential implications of bringing everything down to a financial measure, instead of bringing finance and ecosystems into a "neutral" system with a non-financial basis.
I suspect so.
I think as it is a new concept, time for the "learning curve" would have to be factored in, especially dependent on the policy makers background.
I think Emergy analysis, along with other tools that consider all aspects of an ecosystem could and should be used for decision- and policy-making.
I think it has good potential as it could show policy-makers to what extent we depend on ecosystem services. Most people don't realize how much nature does for us. For example, people might think it's good to protect biodiversity because they like animals, but don't realize that biodiversity provides services such as pollination, pest management or control of other species populations, decomposition, soil renewal, etc. etc.
I think it has potential—I think that we do need to find ways to ensure that ecosystem goods and services are valued appropriately because our current system consistently undervalues natural resources. I don't know enough about the approach yet, but it does seem like it would be a labour-intensive, costly process and therefore I don't know if it would be considered to be a useful tool by policy makers...
I think it has some potential if there is a common agreement of scientifically proven values of solar energy required for each of the wide range of economic and ecologic activities. I think some values are recognized while others are still being studied or simply unknown. This should not make the approach unusable but is an important obstacle
I think linking the concept of basing the value of ecosystem services on total photosynthetic energy required is a bit too esoteric/intractable for many policy makers who are not specialists in the environmental field.
If it is accepted by the scientific and economic communities, then yes, decision- and policy-making will inherently follow it. However, it is too difficult to conceptualize and economists do no adopt it, then it will never be recognized by policy- and decision-makers.
IF this is actually transferred into an easily understood framework that individuals can relate to, then it has value. Particularly if put into the negative value (what is lost).
I'm definitely interested in hearing and learning more about emergy analysis, but from the brief definition given, I have absolutely no idea whether or not this tool would be useful. I guess two questions I have at the moment are: (1) how would emergy analysis get at the trade-offs inherent in making decisions surrounding various resources? (2) can this tool be used in conjunction with other methods?
I'm not sure that embodied solar energy really quantifies all values provided by nature. Specifically where there might be issues of feasibility while humans try to reproduce an ecosystem service. In other words, even with unlimited energy at our disposal, I don't think we could mimic ecosystem services, hence the using the energy embodied in these services to evaluate them may actually undervalue them.
In order for emergy to have applications in policy making I believe that an economic value must be placed on natural goods and services. In our economy, money is, more often than not, the deciding decision making factor.
It could possibly be, however it depends greatly upon the depth analysis covered for the Emergy value of a commodity (i.e. lifecycle, transportation, etc.)
It does not seem as though it takes into account the convenience of accessing the ecosystem services. Somehow it needs to take into account the rate and intensity of these services. Otherwise, the system is extremely biased against non-renewable resources if for example comparing the energy use of a sewage treatment plant to that of a natural ecosystem. Furthermore, estimating the uncertainty in the energy flows would be difficult and be extremely variable between environments. Ultimately, all the ecosystem services within an area of land will be just a measure of what fraction of the incident solar radiation is "utilized" in that area plus the transport of materials, i.e. the carbon and water cycles from other areas. Ultimately getting good estimates of these inputs seems as though it would be very expensive.
It is a complex tool but can be very useful in measuring the full impact of a decision or policy on the

environment and by extension the people who live in that environment.
It offers one consideration for decision-making. However, the value of a service is not simply determined by the amount of energy that goes into it; how rare is the service? how many other beings or processes rely on the ecosystem service?
It seems quite promising, but I can't tell if it will be quantitatively be useful.
it should be used because it informs you of how much energy it actually takes to create natural things
it's handy to use a common denominator—solar energy—for measuring ecosystem goods and services—instead of the current common denominator we use—$$$—that has no real, inherent value. i can see it being very helpful in policy development; we need to find better ways of incorporating environmental realities into economics and politics, and capital, economic, market-driven ways are not adequate.
limited
Looks like it'll be hard to implement and use
may have value—would like to see an example of how it is used to understand the benefits and limitations
Needs to be tested and proven as a useful too. It has potential but you need to demonstrate its usefulness in a very practical and real way.
Not familiar with emergy but any tool that allows policy and decision makers to make more knowledgeable decisions would be useful.
not familiar enough with it to say
Not sure
Only one part of the picture...
Only when it can be communicated to the lowest common denominator will it be a useful tool for policy makers. Policy makers need to find ways to communicate measures and tools to the public.
Policy makers lack the educational background to make informed decisions about matters that include scientific knowledge. I know I have seen the ignorance of those who get jobs doing it. So the potential of any useful tool is limited.
Political decision making is informed by a number of social, economic and environmental metrics (employment, GDP, Bad-air days/human health impacts), using something as esoteric as solar energy is likely not to solicit much of a response.
Possibly good. This survey is not the place to learn about it, so I don't know.
Possibly, depends how presented to those within the system
Possibly?
Pretty complicated.
Seems enormously difficult to calculate or explain—direct and indirect solar energy? One would have to find a very easy way of explaining that to a policy maker or layperson.
Since current valuation systems are predominantly anthropocentric it may be difficult to integrate such ecosystem valuing tools into current thinking.
Since I not a fan of jargon, I would prefer to see simple words to describe what you are describing.
Sounds like it's beyond the scope or interest of most of the small and medium sized businesses that I work with. Who do not even have the resources to maintain a full time environmental person.
Sure, as it is similar to ideas such as life cycle analysis and full cost accounting, which are already being pushed into the decision making realm. But intrinsic and existential valuation cannot be left out.
The general impression is given based on the state of use of scientific knowledge / practice/general trends of the policy makers in Bangladesh. The method sounds technically good, however, will be difficult for the policy makers to understand. Policy makers are politicians, hence, their tool for making decision will be based on economic values. On the other hand, any policy taken at the highest level should be understood or worked out at the field level. Such technical system of valuation may not be understood by the less disadvantaged people living around any particular ecosystem (i.e. forest).
The tool seems like it would give a good estimate of the biophysical energy inputs associated with various forms of natural capital. However, it appears that this tool does not incorporate a measure of the economic

value associated with the natural capital and should therefore ideally be supplemented with another economic analysis if possible.
The use of any tool, that the results can easily be conveyed to policy makers, is a useful tool
This appears to be a tool to convince "others" of the value of ecosystem services. While it may be a good tool.........do we need it still? Aren't government, business and individuals aware of these benefits—but just slow to actually act on protecting these? We need action. If this tool can move society towards "action" then I would support its use
Unaware of emergy analysis
Unknown, first I've heard of it.
Yes—it summarizes ecosystems services into numbers, which is useful for policy-makers. It runs the inherent risk of leaving out certain considerations (such as the cultural value of ecosystems and ecosystem services), and must therefore not be taken as a panacea; but this should not be perceived as a downside, merely a limitation to keep in mind in its use. I think it would be quite labour-intensive to come up with emergy analyses for various ecosystem services—this might be its greatest disadvantage.
Yes, but it still leaves out intrinsic values such as the existence values associated with natural areas that provide spiritual well-being, recreational opportunities, etc.

Table 11.20 Would you consider using emergy analysis in the future? If yes, for what applications? If no, why not?

As a consultant yes, evaluation of risk
Assuming that the methods for emergy analysis are well developed and robust, I could see using the information when conducting environmental assessments or to calculate the benefits of green design.
Clean drinking water seems reasonable—how energy and infrastructure would it take to generate the clean water that arrives due to evaporation. However, this still leaves out any soil or plant filtration.
Definitely, we should use this analysis in the future. Please, see my comment (above, at point 1). At first, the tool (emergy analysis) seems complicated but I think we should implement it at primary and elementary schools. From here, parents and the general public should start knowing about it. I suggest this because politicians and decision makers are orthodox and don't like new ("complicated") tools (they will inevitably would keep using economic $$ tools). Then we should promote it at all educational levels and society as a whole should demand decision makers to use it.
Don't know
Don't know
Environmental impact assessments, particularly for projects in the primary resource and extractive industries
For evaluating seemingly equal alternatives when designing and industrial process/facility, but not globally, for determining true cost of goods and services. I think that using it to determine cost/price of consumer-level goods and services would essentially undermine the economy— it would require a massive restructuring of the financial world, a cost which would be borne largely at a grassroots level.
I could see using emergy to "see" the impacts of various things in my day to day life. I would not want to spent lots of time dealing with the tool. Something that provides a quick summary would be more useful.
I don't know
I don't know, I would need to look at the available information.
I personally do not conduct such analyses, but I would mention it to colleagues if the opportunity arose.
I think it would be too complicated. Decision-makers don't even make rational decisions half the time.
i would consider it, but i am not involved in policy making, but it should be brought up in education to future policy makers

I would consider using emergy as a guideline and support tool and feel there is merit in analyzing what emergy can tell me.
I would definitely consider using emergy analysis as part of a "analysis package." That is, I would use it in conjunction with other valuation methods to try to determine the correct value for ecosystem services.
I would like to learn more about it.
I would not consider using this. Rather I would suggest for a tool that incorporates three issues (1) value by the people at the local level, (2) some sort of economic measure and (3) some scientific / ecological (that local people can adhere to) measures.
I would use emergy analysis as one environmental performance indicator in LCA, along with measures of energy or exergy demand, abiotic and biotic resource dependencies, and emission intensities. It is my strong opinion that nuance is preferable to aggregation, which results in non-trivial information loss and hence strips unidimensional metrics of their legitimacy.
I would use it for calculating the net losses due to urban expansion. I would not use it for remote disturbances or areas. As remote disturbance areas are extremely unique and are already subject to, too many blanket type policies and regulations which in some cases don't fit the small niche eco-regions.
I would, however application would lean more towards non-essentials. I know inherently there is a strong impact on food consumption preferences given this method as well—and that can in some cases be a cultural barrier.
If it came up, yes, but right now I'm not sure.
if it yields results that are easily understandable and communicable to non-technical audiences
If making a decision with economical implications then I would look into it
If the opportunity arises, I will gladly use emergy analysis.
I'm not sure. I haven't really explored work that would utilize such an approach yet.
Likely not—very difficult concept to communicate to senior managers and political decision makers.
maybe—need more information
Maybe. If there was a practical application then yes.
Maybe. So...we convert everything to solar emjoules? what about that "transformity" issue. Why not just stick to LCA...Do we need to reduce everything to emergy measures?
More likely to use ecological footprint. Both should be used in part with other tools like LCA which have a more holistic approach
N/A
no, not applicable
No, not applicable to my current field of work.
No. I don't know anything about it.
No. Too complicated for basic environmental management for firms under 500 employees who do not even consider that they have an environmental impact.
No. I'd be hard pressed to see an application in my decision making around environmental issues / choices. Something embodies a lot of solar energy? Sure, but in terms of how that relates to its value, I'm not sure the connection works.
No. Not proven at this time.
nope, plenty already out there with a more common track record which has value in the public eye, whether that's a good thing or not, it's sadly an argument with policy-makers and business people.
Not at all—hedonics would, frankly, be of more practical value to political decision-making.
Not particularly useful in my line of work—but good to know about
Not personally, but I would like to see the results of such.
not sure
Not sure
Not sure and I do not know enough about it at present.

not sure, see above
Perhaps—valuing urban forest benefits;
Perhaps, as a contribution to a larger economic analysis and decision-making process.
possibly
Possibly. Need to know more about it.
potentially— need to learn more
Potentially.
Sure, for interesting facts. Somewhat difficult to identify specific uses.
This is not in my field, but otherwise I would!
too academic for my work setting. we have an energy audit for corporate buildings and a detailed ghg emission inventory, and reduction plan. tangible, understandable, practical.
Unaware of emegy analysis
Valuing the environment will take a number of different tools used in combination to get a better idea of the total value held by ecosystem goods and services. Considering most of the models and tools we use presently are riddled with assumptions, it's not just the tool that will help us, but also the operator making sure the tool is used for the proper purpose and that any results are communicated in a manner that can be acted upon. Emergy analysis sounds interesting, but I would need to have the criteria spelled out for me so I can better understand where I can use this analytical tool and pitfalls that might be associated with it. I know from my own work with Discrete Choice Experiments that you will always get an answer from any model you build, it's just whether or not the answer really means anything. Also, I would love to know how emergy analysis can fit in with other existing techniques for valuing the environment.
We are currently looking at Eco Value, InVest and Marxan but we are not yet set on those three
When setting up sustainable communities that are not plugged into the grid these types of analysis may be useful. Specifically, ecosystem services evaluation will be useful in creating policies for homeowners wishing to live in a community that frees them from the oil bill, the power bill, and in some cases the water bill. The inherent value of living in such communities will be the basis for attracting people of low to moderate income who are ready to purchase properties that are environmentally and economically sustainable. The value of not worrying about whether or not your home will be heated during the winter months will be evaluated too. Truly sustainable systems consider the environment first, then social responsibility and lastly economic components. The solution to environmental issues can never spring from catering to the perceived needs of the wealthy or from some singular hermit who lives in an off grid shack. The solution must flow from the diverse yet prevalent needs of everyday people—who by the way are the majority.
Work in the energy sector
would have to educated myself further
Yes
Yes
Yes—if I knew more methodology about how to employ it. I see numerous applications—i.e. use as a to find a baseline figure of the amount of emergy input and output by national Parks and other conservation areas (vs. input output of urban and industrial areas), potential use in EIAs to evaluate the impact of cumulative effects of industry, and potentially in the "green" housing industry to provide a means to evaluated how green a new housing development is (if a new green housing subsidy plan is ever introduced by the F/P/T and/or Municpal governments.
Yes, for analysis of the costs of various forms of transportation, i.e. automobiles vs. public transit. However, I think it would be difficult to relate it specifically back to the source of the externalities associated with this topic. From my understanding, they currently use the "cost" that pollution and air quality (see Litman), but I'm not sure how emergy analysis could be linked into the analysis.
Yes, for decisions on what materials to use for a new product.
Yes, for determining the full impact of development and its cost associated to societal needs and ecological services.

Yes, I would use it in the valuation of ecosystem services for integrated environmental and economic accounting.
Yes, if it was simple.
Yes, to evaluate built form.
Yes, to find solutions to sustainably using natural resources.
yes, we often to cost benefit analysis of developments. It would help us quantify environmental and habitat protection
Yes. If the land use of a natural ecosystem is to be disturbed by a development for the purpose of providing services that could also be provided by the ecosystem, or for exploiting the land for the provision of energy.
yes. Probably with regards to sustainability in resource consumption.
Yes... if I were in any position to make decisions related to natural resource use. i.e. where/how to get source materials for products or construction, to make policy decisions regarding the future of natural areas (particularly source water management), etc.
Yes...It would be an interesting supplementary tool for socio-economic purposes. I could see it being used in the evaluation of alternatives related to land management decisions. Again, I struggle with the notion that all necessary data will be available (and at reasonable cost).
yes; although at present i cannot think of specific applications. perhaps in analysis of government or private business policies and practices; as a way to counter-act the regular economic market-driven practices

Table 11.21 Do you feel that our natural environment is threatened by human expansion and activities?

Answer options	Response frequency (%)	Response count
Yes	99.2	118
No	0.8	1
	answered question	119
	skipped question	18

Table 11.22 Do you feel that the value of goods and services that we access through the markets are representative of their true value and cost?

Answer options	Response frequency (%)	Response count
Yes	1.7	2
No	98.3	117
	answered question	119
	skipped question	18